RTCA, Inc.
1828 L Street, N.W. Suite 805
Washington, D.C. 20036

MINIMUM AVIATION SYSTEM PERFORMANCE STANDARDS (MASPS) FOR THE HIGH FREQUENCY DATA LINK (HFDL) OPERATING IN THE OPERATING IN THE AERONAUTICAL MOBILE (ROUTE) SERVICE (AM (R)S)

RTCA/DO-277
March 5, 2002

Prepared by SC-188

Copies of this document may be obtained from

RTCA, Inc.
1828 L Street, NW, Suite 805
Washington, DC 20036

Telephone: 202-833-9339
Fax: 202-833-9434
Internet: www.rtca.org

Please call RTCA for price and ordering information.

FOREWORD

This document was prepared by RTCA Special Committee 188 (SC-188). It was approved by the Program Management Committee on March 5, 2002.

RTCA, Incorporated is a not-for-profit corporation formed to advance the art and science of aviation and aviation electronic systems for the benefit of the public. The organization functions as a Federal Advisory Committee and develops consensus based recommendations on contemporary aviation issues. RTCA's objectives include but are not limited to:

- coalescing aviation system user and provider technical requirements in a manner that helps government and industry meet their mutual objectives and responsibilities;
- analyzing and recommending solutions to the system technical issues that aviation faces as it continues to pursue increased safety, system capacity and efficiency;
- developing consensus on the application of pertinent technology to fulfill user and provider requirements, including development of minimum operational performance standards for electronic systems and equipment that support aviation; and
- assisting in developing the appropriate technical material upon which positions for the International Civil Aviation Organization and the International Telecommunication Union and other appropriate international organizations can be based.

The organization's recommendations are often used as a basis for government and private sector decisions as well as the foundation for many Federal Aviation Administration Technical Standard Orders.

Since RTCA is not an official agency of the United States Government, its recommendations may not be regarded as statements of official government policy unless so enunciated by the U. S. government organization or agency having statutory jurisdiction over any matters to which the recommendations relate.

Appendices C and E are normative appendices.

This page intentionally left blank.

TABLE OF CONTENTS

APPENDICES

TABLE OF FIGURES

TABLE OF TABLES

1 PURPOSE AND SCOPE

1.1 Introduction

This document contains minimum aviation system performance standards for communications utilizing High Frequency Data Link systems for the air-ground communications subnetwork in an Aeronautical Telecommunications Network (ATN) environment. The FANS 1/A data link environment is also addressed. These standards specify characteristics that should be useful to designers, installers, manufacturers, service providers and users of systems intended for operational use within the United States National Airspace System (NAS). Where systems are global in nature, the system may have international applications that are taken into consideration.

Compliance with these standards is recommended as one means of assuring that the system and each subsystem will perform its intended function(s) satisfactorily under conditions normally encountered in routine aeronautical operations for the environments intended. The MASPS may be implemented by one or more regulatory documents and/or advisory documents (e.g., certification, authorization, approval, commissioning, advisory circular, notice, etc.) and may be implemented in part or in total. Any regulatory application of this document is the sole responsibility of appropriate governmental agencies.

It is anticipated that regional service contracts may require additional declaration of performance values for smaller coverage volumes using the methodologies described in this document and its appendices.

Section 1 of this document describes a generalized High Frequency Data Link (HF Data Link) System, and the data link environment in which it is used, and provides information needed to understand the rationale for system characteristics and requirements that are stated within this document. This section also contains typical applications and envisioned operational goals and assumptions necessary to establish a basis for the subsequent sections.

Section 2 defines the general requirements of an HF Data Link subnetwork, specific requirements for its interfaces, and specific minimum Installed Communications Performance (ICP) requirements when viewed as an air/ground subnetwork of an end-to-end data network. The ICP requirements include delay, integrity, availability and continuity of service parameters.

Section 3 establishes requirements for specific information that must be provided in the system-specific attachments and establishes pro-forma tables and methodology by which that information is to be provided. The purpose of this disclosure is to provide confidence that the subnetwork design will achieve the "Point B-to-Point C" performance specified in Section , prior to the approval of that system for HF Data Link. A system-specific attachment will not require RTCA approval or publication. The ultimate proof of performance at the subnetwork level is the verification procedures of Section 4.

Section 4 describes procedures recommended for verifying compliance of the subnetwork and its elements with the minimum performance requirements in Section 2.

Appendices of this document are structured to contain either normative or informative material, and are so identified in each case. Normative appendices contain material, such as descriptions of acceptable analytic methodologies, where the inclusion of such material in the main body of the document would be cumbersome. The main body references appendix material wherever appropriate.

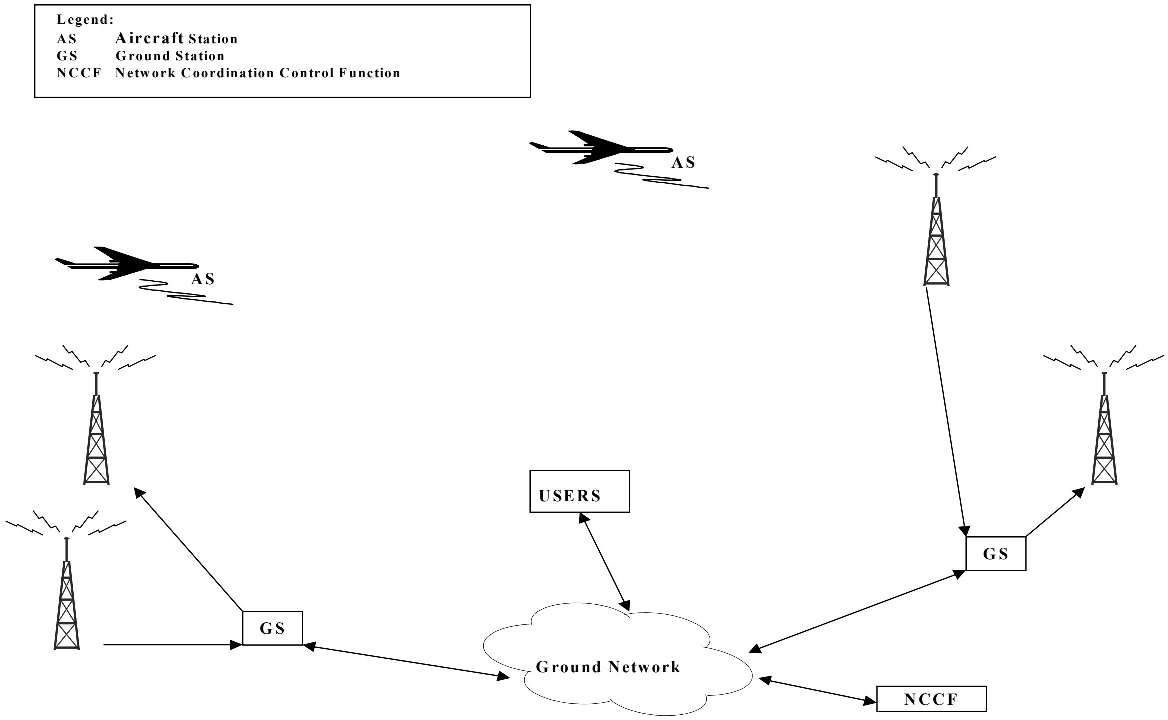


Figure 1-1: High Frequency Data Link System Elements

The words "subnetwork and its elements" as used in this document are intended to include all components that make up a major independent, necessary and essential functional part of the air-ground communications subsystem so that the system can properly perform its intended functions. If any element includes computer software, then the guidelines contained in RTCA DO-178B should be considered for ground-based, as well as airborne, applications. Users of this document are urged to become familiar with the tutorial material on HF Data Link communications and the various aeronautical communications networks contained in Appendix F.

1.2 System Overview

1.2.1 System Architecture

The HF Data Link system conforms to International Civil Aviation Organization (ICAO) Chapter 11 SARPs (see Section 1.7 for reference documents). A brief overview of the HF Data Link architecture is provided in Appendix F. Additional detail is contained in the ICAO Document 9741.

1.2.2 ICAO Global CNS/ATM and System Performance Concepts

The goal of the ICAO Global Communications, Navigation, and Surveillance/Air Traffic Management (CNS/ATM) concept is to implement a global system with cost-effective communications, navigation, and surveillance systems integrated with appropriate automation and procedural solutions leading to major enhancements in air traffic management (ATM). A primary emphasis is also placed on digital communications, supporting information transfer via both data link and voice. The ICAO concept for navigation and communications solutions emphasize satellite systems (GNSS and AMSS) for global coverage, and line-of-sight systems for high-traffic volume communications in the terminal area. However, alternative means of communications, such as HF Data Link, are also considered to be candidates for the CNS system of the future.

Required Communications Performance (RCP) is a statement of the end-through-end communications performance necessary for flight within a defined airspace, or to perform a discretely defined operation or procedure. A RCP is determined by cognizant authorities in consideration of air traffic operations and flight standards, target levels of safety, separation assurance, and functional hazard analysis associated with the airspace, operation or procedure. Thus, RCP is independent of the technology, or combination of technologies, that may be utilized for communications. An assumed concept of RCP and its relationships with the performance requirements of this document are contained in Section 1.5.1.

1.2.3 HF Data Link System Overview

HF Data Link is the designation by ICAO for two-way communications via HF radio frequencies pertaining to aeronautical safety and regularity of flight on national or international civil air routes. HF Data Link operates in the Aeronautical Mobile (R) Service (AM(R)S) High Frequency bands. The AM(R)S HF bands are intended for aeronautical communications for aircraft flying on civil aviation routes ("on-route"), and is commonly used to distinguish aeronautical safety communications from other communications that might be conducted via HF radio frequencies.

An end-to-end HF Data Link data communications link consists of four principal elements – aircraft equipment, ground station equipment, ground network and ground user facilities – as shown in Figure 1-1.

In addition, this MASPS addresses radio-frequency propagation paths and associated control facilities such as a Network Coordination and Control function, (NCCF).

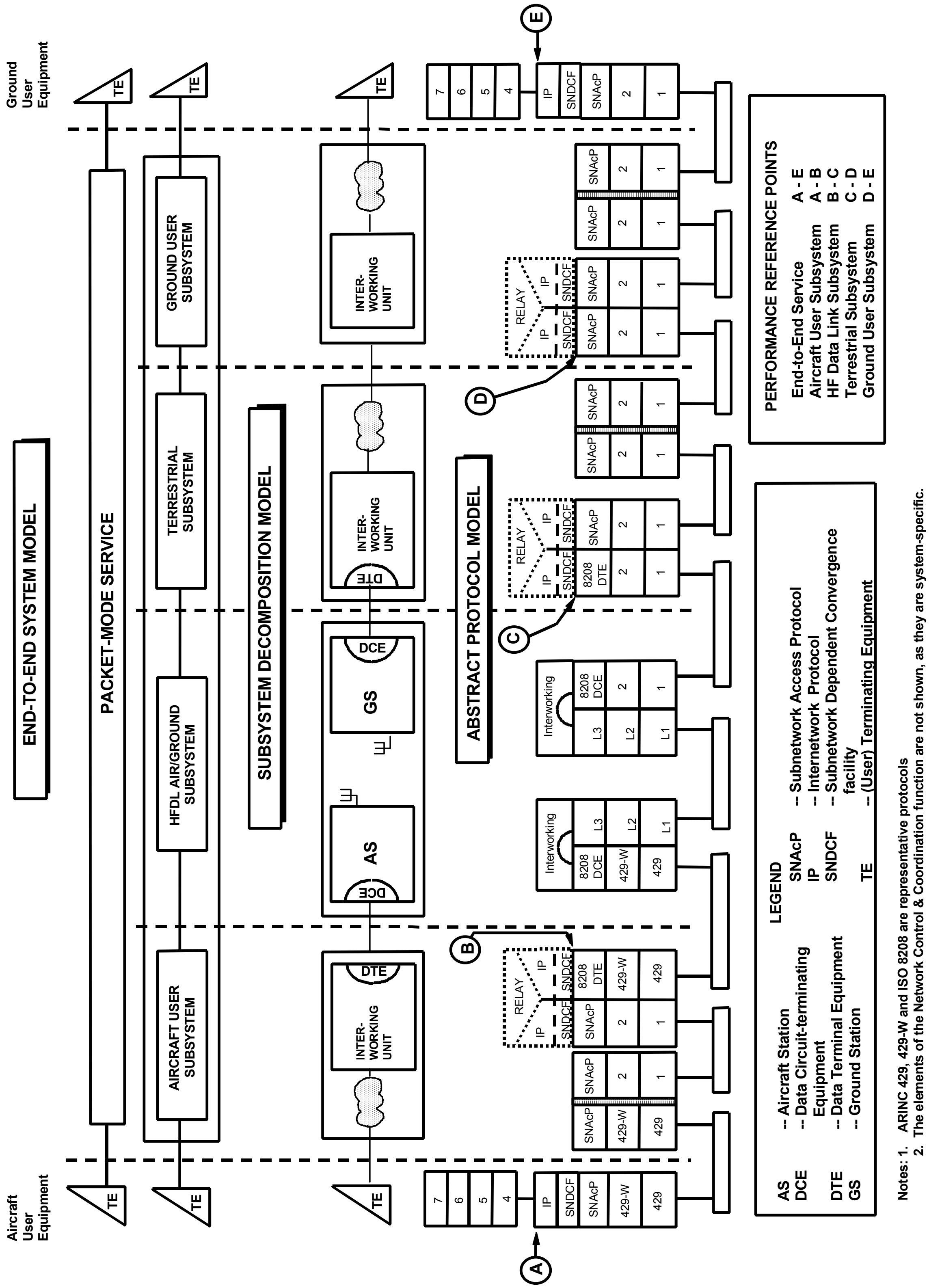


Figure 1-2: End-to-End Packet-Mode Services System Structure

1.2.4. End-to-End Communications Environments

Current aeronautical data communications are supported by message and/or packet-switching networks. A representative end-to-end data link consisting of aircraft, air/ground, terrestrial and ground user subnetworks is depicted in Figure 1-2. From the perspective of "plug-in" communications links, the end-to-end performance can be defined at the Network layer level, indicated in the Figure by Point A and Point E. An "end-through-end" overall communications system performance requirement would also include the effects of the higher protocol layers and the terminal equipment (end systems). This document addresses only the HF Data Link air/ground subnetwork portion, for which the reference points are indicated by Point B and Point C of Figure 1-2. These points are referred to as Point B and Point C throughout this document.

1.2.4.1 The Aeronautical Telecommunications Network (ATN)

The ATN architecture is predicated on data communications standards developed by the International Organization for Standardization (ISO) which apply the principles of the Open System Interconnect (OSI) model. High-level requirements for the ATN have been published by ICAO as SARPs and the details are available as an ICAO Manual, Document 9705.

1.2.4.2 FANS 1/A Data Link

FANS 1/A data links utilize the character oriented protocols developed for the Aircraft Communications Addressing and Reporting System (ACARS). ACARS is a VHF data link system developed by the commercial air carrier industry that has grown to a system of global dimension since its introduction in the late 1970's. The protocols developed for ACARS have been updated for use on VHF, AMS(R)S, and HF Data Link. Currently, over 5000 aircraft are fitted with ACARS equipment. The FANS 1/A aircraft equipment suite also includes communication management units capable of supporting data link operations and interfaces with other avionics equipment (e.g., flight management computers).

1.2.5 HF Data Link Service Responsibilities

In contrast to most air traffic communications services, HF Data Link services are provided almost exclusively by private industry. Access to HF Data Link services may be contracted for by CAAs and aircraft operators directly with the service provider. The service provider oversees the management of and access to the HF Data Link Subnetwork and/or certain of its elements. They must

(1) comply with regulatory requirements;
(2) warrant performance;,
(3) ensure availability and integrity within their declared service coverage areas;
(4) accept priority rules for allocation of system resources;
(5) supply acceptable system monitoring and control.

For safety communications, the aircraft owner/operator is ultimately responsible for

(1) the correct operation of the airborne element;
(2) entering into an agreement for the appropriate levels of service for its flight operations.

1.3 Operational Applications

1.3.1 Air Traffic Services

Air Traffic Services (ATS) currently include Air Traffic Control (ATC), the Flight Information Service and the Alerting Service. The ATS data link applications utilizing HF Data Link were initially developed primarily for oceanic and remote airspace where conventional line-of-sight communications (e.g., VHF radio) and surveillance (e.g., radar) are not available.

1.3.2 Aeronautical Operational Control

Aeronautical Operational Control (AOC) uses data communications for applications including the air-ground exchange of accurate and timely information, coordinating activities in the interests of passenger, baggage, cargo and mail; and to enhance flight safety, punctuality, and cost reduction. AOC, along with ATS, is a safety service, and is supported by HF Data Link.

1.3.3 Non-Safety Communications Services

Non-safety communications are prohibited on frequencies designated AM(R)S, and hence are not supported by HF Data Link service described in this document. Non safety communications include Aeronautical Administration Communications (AAC) and Aeronautical Passenger Communication (APC).

1.3.4 Data and Voice Communications

Currently, the primary emphasis of HF Data Link users and providers is on data link applications because of the efficiency and integrity afforded by data communications, and because of the operational advantages of new automation services such as Automatic Dependent Surveillance (ADS) which are enabled by data communications. However, voice communications will be necessary throughout the foreseeable future for emergency, urgent and non-routine communications. The initial ATC data link services, such as ADS and Controller-Pilot Data Link Communication (CPDLC) will require a backup voice communications capability.

However, this document addresses only data communications via the HF Data Link subnetwork.

1.4 Operational Goals

As Communications, Navigation and Surveillance systems evolve toward the Global CNS/ATM concept, the benefits accruing to the users of those systems should remain paramount in consideration of their characteristics. One fundamental dimension in quantifying user benefits can be expressed initially in terms of reduction of separation standards in airspace having predefined route structures, and subsequently in terms of substantially less route structuring in allowing optimized flight profiles (so-called "free flight").

1.4.1 Coverage

The goal of the civil aviation community is to achieve worldwide, high-quality safety (ATS/AOC) communication services from the surface to at least 21,350 meters (70,000 feet).

1.4.2 Compatibility and Interoperability

An HF Data Link system is expected to be compatible and interoperable with external systems for all levels of users. This requires implementation of well-defined gateways and peer-to-peer protocols. Therefore, HF Data Link must provide standard network interfaces between aircraft and associated ground systems on a global basis. For packet data transmissions, an HF Data Link system is expected to implement the OSI Reference Model, and will ultimately be integrated in the Aeronautical Telecommunications Network (ATN).

HF Data Link routing and addressing schemes will be compatible worldwide. The twenty-four (24)-bit International Civil Aviation Organization (ICAO) standard aircraft address will be implemented throughout HF Data Link to ensure compatibility among organizations and subsystems.

1.4.3 Priority And Precedence

A system that provides HF Data Link is expected to provide mechanisms by which only safety communications receive priority access to the communications resources of the HF Data Link subnetwork.

1.4.4 Failure Modes, Warnings, and Flags

The goals for failure modes, warnings, and flags in HF Data Link communications are set by the need to assure that users of the facilities are made aware of a degraded status of the communications system, so that alternative systems and/or procedures can be employed as necessary. For an automated air/ground communications subnetwork used in the ATN environment, this requirement may be met by the existence of the connectivity (join/leave) event notification and, in certain installations, by annunciation to the flight crew.

1.4.5 Human Factors Considerations

Human factor considerations in HF Data Link communications are set by the need to maximize the utility of communications to pilots, controllers and other users of the system; to minimize additional workload; and to minimize the risk of miscomprehension or misuse. Human factor considerations are normally associated with end-user requirements, as contrasted with elements of an end-to-end system; however, certain aspects may be controlled by an air/ground subnetwork, such as channel selection. Specific human factors guidelines that may be pertinent to specific data link implementations can be found in RTCA DO-238, Human Engineering Guidelines for Data Link Systems.

1.5 Assumptions

1.5.1 Assumptions Regarding the Required Communications Performance (RCP) Concept

Required Communications Performance (RCP) is a statement of the end-through-end communications performance necessary for flight within a defined airspace, or to perform a discretely defined operation or procedure. RCP is a set of requirements based on the safety objectives needed for a particular operation or procedure, and is independent of the technology or combination of technologies that may be utilized for communications.

This document provides a process by which a service provider can produce estimate(s) of the Installed Communications Performance (ICP) achieved by their HF Data Link. The ICP(s) established in accordance with this MASPS will then be combined with the ICP(s) of the other network pieces comprising the end-to-end communications system. This document describes the content of a system-specific attachment containing a declaration of global or regional ICP performance.

Service contracts may require greater specificity of ICP data than the data disclosure required by this MASPS. In particular, full empirical probability distributions for delay may be required, and more geographical and temporal points for which delay, availability and continuity of service data are provided may be required.

Additional information regarding the development of RCP parameters and the determination of ICP parameter values may be found in RTCA DO-264.

1.5.2 Assumptions Regarding the ATN

It is assumed that the ATN's Subnetwork Dependent Convergence Function (SNDCF), which is located external to the HF Data Link air/ground subnetwork (i.e., outside of Point B and Point C), has the responsibility for mapping the ATN priority structure to the HF Data Link priority structure.

1.5.3 Assumption Regarding Use of HF Data Link Avionics

This document assumes that the HF Data Link avionics are enabled for communications on the HF Data Link subnetwork 100% of the time.

Note:

This assumption is necessary to allow quantitative requirements to be established for the HF Data Link communications parameters independent of current operational procedures. As of early 2002, ATC procedures required that HF voice communications be used for certain trans-oceanic operations. Pilot-initiated use of HF voice communications automatically disables HF Data Link communications for that aircraft. This has the effect of reducing the availability of HF Data Link from the perspective of that individual aircraft. It is anticipated that growth in the use of data-link communications will eventually replace these current procedures.

1.5.4 Assumption Regarding Independence of Avionics and Ground System Failures

The partitioning activities discussed in Section 3 assume that failures of the aircraft station and the HF Data Link network infrastructure are independent.

1.6 Verification Procedures

The verification procedures specified in this document are intended as an acceptable means of demonstrating compliance with the performance requirements. Although test procedures are normally associated with performance verification, it is recognized that other methods (e.g., analysis, simulation, inspection) may be used, and may be more appropriate to the large-scale systems addressed in this MASPS. However, it is desirable that such other methods be validated by procedures involving actual measurements of the system performance.

Alternatives to the procedures specified herein may be used if it can be demonstrated that they provide at least equivalent information. Subsystem verification is useful as subsystems are added during system buildup and to ensure continued subsystem performance as it relates to overall system performance.

1.7 Reference Documents

For certain requirements this document makes reference to other documents by shorthand identifiers. These are fully identified as follows:

Identifier	Title
RTCA DO-160D	Environmental Conditions and Test Procedures for Airborne Equipment
RTCA DO-178B	Software Considerations in Airborne Systems and Equipment Certification
RTCA DO-265	Minimum Operational Performance Standards (MOPS) for Aeronautical Mobile High Frequency Data Link (HFDL)
RTCA DO-270	Minimum Aviation System Performance Standards (MASPS) for Aeronautical Mobile –SATELLITE (R) Service (AMS(R)S) as used in Aeronautical Data Links
RTCA DO-237	Aeronautical Spectrum Planning for 1997-2010
RTCA DO-238	Human Engineering Guidance for Data Link Systems
RTCA DO-240	Minimum Operational Performance Standards (MOPS) for Aeronautical Telecommunication Network (ATN) Avionics
RTCA DO-264	Guidelines for the Approval and Use of Air Traffic Services Supported by Data Communications
Chapter 11 SARPs	ICAO Annex 10, Volume III, Part 1, Chapter 11, "HF Data Link "
Document 9705	Manual of Technical Provisions for the Aeronautical Telecommunication Network (ATN)
Document 9741	Document 9741-AN/962, First Edition - 2000 ICAO Manual on HF Data Link

1.8 Definition of Terms

A list of acronyms and a glossary of key terms is contained in Appendix A.

This page intentionally left blank.

2 SUBNETWORK PERFORMANCE REQUIREMENTS

This section specifies the general requirements and specific Installed Communication Performance (ICP) requirements for an HF Data Link packet-mode subnetwork. Figure 2-1 shows the reference points (B and C) for performance requirements, corresponding to the same points in Figure 1-2.

Note: The protocol stacks external to the subnetwork are necessary to interface with the AS and GS, and can be conceptualized as perfect DTE test sets having negligible contributions to performance factors.

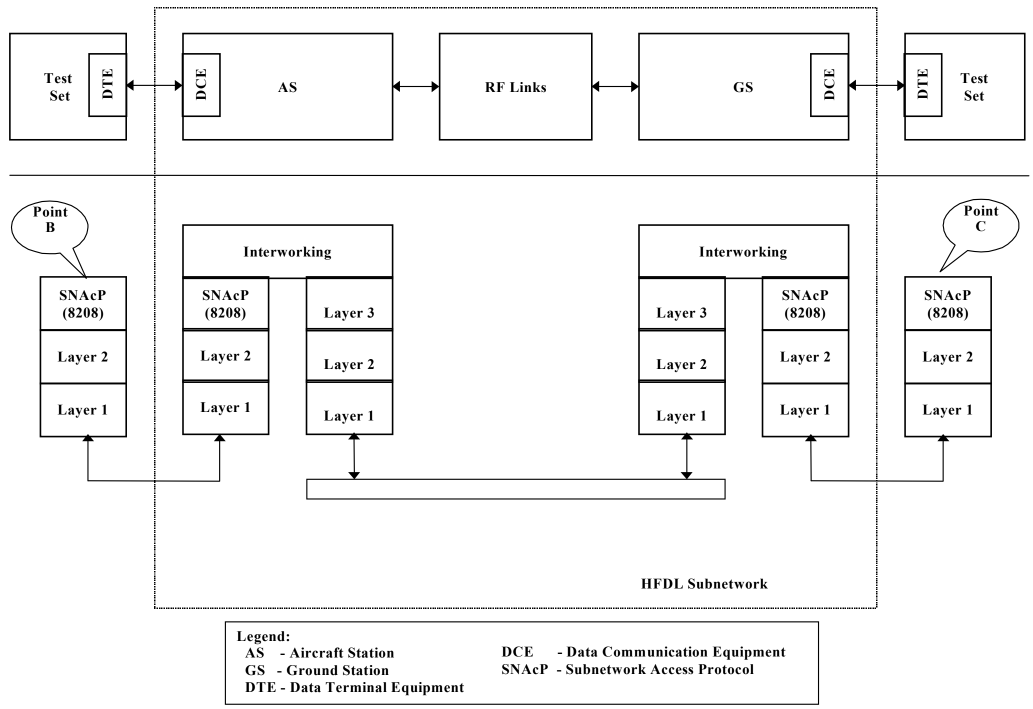


Figure 2-1: HF Data Link Subnetwork and Performance Reference Points

2.1 General Requirements

The HF Data Link subnetwork shall meet all pertinent airworthiness, human factors and operational requirements including alerts, controls and frequency management considerations.

Requirements relating to carriage of HF Data Link equipment on aircraft and implementation of ground infrastructure supporting HF Data Link shall be in accordance with national requirements, regional agreements or international agreements, including the level of system capability, as appropriate for Air Traffic Service operations and Aeronautical Operational Control.

2.2 Specific Requirements

Specific requirements for HF Data Link are described in this section. Quantitative requirements are contained in Table 2-1. Table 2-1 will be filled out when applying for ATS approval for any given coverage area.

Table 2-1: Quantitative Requirements for System Characteristic Declaration

Symbol	Characteristic	Paragraph Ref.	Declared Value
no symbol	ICAO Chapter	1.2.1	
	Transmit and Receive frequencies	2.2.2	
Ω	Coverage volume	2.2.3	
no symbol	Number of HF Data Link Priority Levels	2.2.4.1	
-----	HF Data Link 95% Transfer Delay	2.2.5.1.3 2.2.5.1.4	
no symbol	A/G Lowest safety Priority	2.2.5.1.3 2.2.5.1.4	
no symbol	G/A Lowest safety Priority	2.2.5.1.3 2.2.5.1.4	
no symbol	A/G Highest safety Priority	2.2.5.1.3 2.2.5.1.4	
no symbol	G/A Highest safety Priority	2.2.5.1.3 2.2.5.1.4	
no symbol	Block Integrity (128 octets)	2.2.5.2	
T_{OD}	Service Outage Time Threshold	2.2.5.3.1	
A	Availability	2.2.5.3.2	
T_{COS}	Continuity of Service Interval	2.2.5.4.2	
T_{SI}	Service Interruption Time Threshold	2.2.5.4.1	
COS	Continuity of Service	2.2.5.4.2	
T_{DET}	Maximum Service Outage Detection Time	2.2.6.1	
no symbol	ATN-compliant interface protocol	2.2.7.1	
no symbol	Connection Establishment Delay (95th percentile)	2.2.7.3.1	

2.2.1 Standard Operating Conditions

At the HF Data Link system level, the standard operating conditions shall be as established by the traffic model defined in accordance with Section 2.2.5.1.1, and the 50th percentile RF link performance as established by Appendix B. The minimum acceptable traffic model shall be as defined in Appendix E.

2.2.2. Spectrum Requirements

The HF Data Link system shall operate in frequency bands available to the Aeronautical Mobile (R) Service. The frequency bands are 2.8 – 22 MHz. Each element of the HF Data Link subsystem (including AS and GS) shall conform to applicable International and National (e.g. FCC and ITU) Radio Regulations.

2.2.2.1 Emission Designators

The emission designator for HF Data Link (AS and GS) transmissions shall be 2K80J2DEN.

2.2.2.2 Interference

This section addresses the high-level requirements relevant to potential harmful interference within the HF Data Link subnetwork.

2.2.2.2.1 Emissions

While operating in the data mode, the HF Data Link shall continue to meet the spectrum mask defined in ICAO Annex 10 chapter 11 section 11.3.1.11, as follows:

The peak envelope power (P_p) of any emission on any discrete frequency shall be less than the peak envelope power of the transmitter, see ICAO SARPs, Section 11.3.1.11, in accordance with the following:

a) on any frequency removed by 1.5 kHz or more up to 4.5 kHz from the SSB assigned frequency: at least 30 dB;

b) on any frequency removed by 4.5 kHz or more up to 7.5 kHz from the SSB assigned frequency: at least 38 dB;

c) on any frequency removed by 7.5 kHz or more from the SSB assigned frequency : at least 43 dB for the AS;

d) on any frequency removed by 7.5 kHz or more from the SSB assigned frequency, for GS with transmitter power from power up to and including 50 Watts, the attenuation shall be at least $-43+10\log_{10}(P_p)$ dB. For transmitter power more than 50W, the attenuation should be at least 60 dB.

The peak envelope power supplied to the antenna transmission line shall not exceed a maximum value of 6kW as provided for in the ITU regulations.

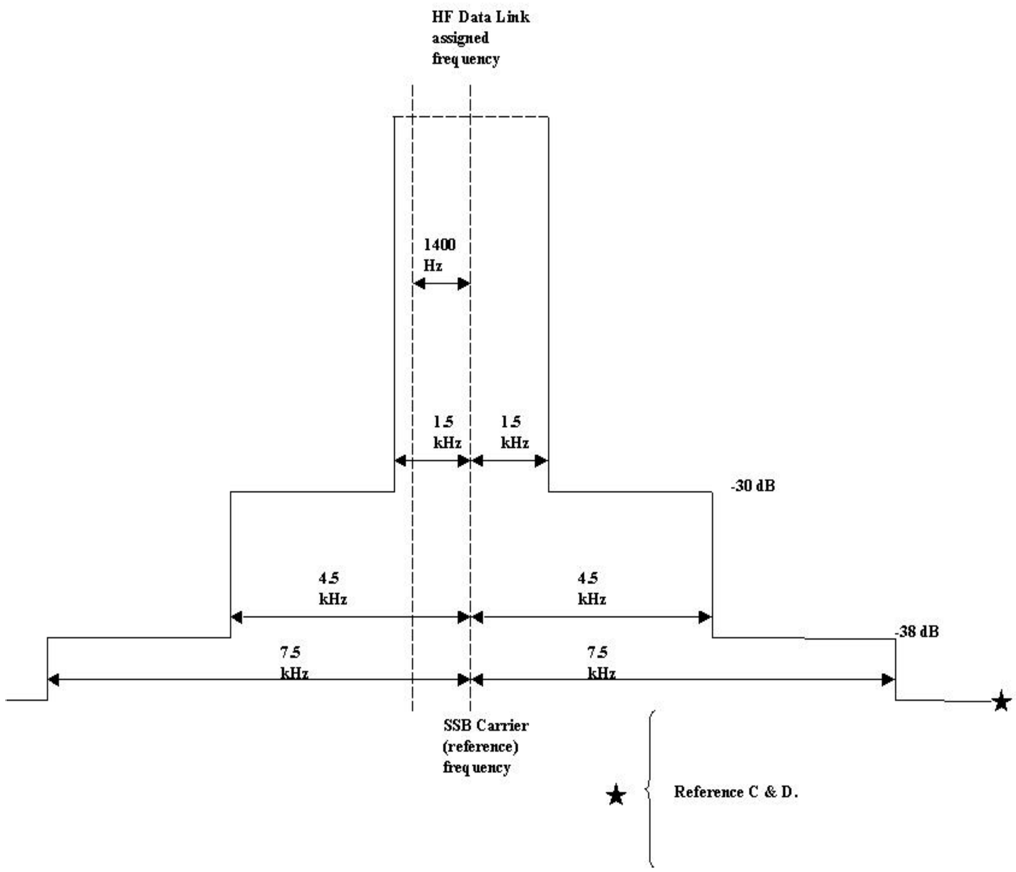


Figure 2-2: Transmit Spectrum Limits

2.2.2.2.2 Undesired Signal Rejection

HF Data Link AS and GS receivers shall attenuate undesired signals in accordance with the following

a) On any frequency fc and (fc – 300 Hz) or between (fc + 2900 Hz) and (fc + 3300 Hz); at least 35 dB below the peak of the desired signal level

b) On any frequency below (fc – 300 Hz) or above (fc + 3300 Hz) at least 60 dB below the peak of the desired signal level where fc is the desired carrier (reference) frequency

2.2.3 Coverage Volume

The coverage volume for HF Data Link is defined as that volume of airspace delineated by an area of the Earth's surface and an altitude above the Earth's surface, within which the ICP and service requirements of this document are satisfied. The HF Data Link service provider shall declare the boundaries of the total planned coverage volume and the specific subset of the total coverage volume for which operational approval is expected as part of the normative attachment.

Note:It is expected that the coverage of the HF Data Link subnetwork will have little dependence on the altitude of user aircraft.

2.2.4 Priority, Precedence and Preemption

Each element of the HF Data Link Subsystem (including AS and GS) shall conform to applicable International and National Radio Regulations and aviation regulations governing the precedence and protection of aeronautical mobile safety communications. Each HF Data Link service provider shall address each requirement of this section in its system-specific normative attachment with a complete description of the mechanisms enabling the system to meet the requirements.

2.2.4.1 Priority Levels

The HF Data Link system and its elements as appropriate, shall support not fewer than three priority levels at the subnetwork interfaces. Messages and data blocks that are submitted for transmission and not identified with one of these pre-established priorities shall not be transmitted.

Note: For the purpose of this document the three HF Data Link priorities are designated as Distress/Urgency (highest safety priority), Flight Safety, and Other Safety (lowest safety priority).

2.2.4.2 Precedence

Each AS and GS shall ensure that higher priority blocks are not delayed by the transmission and/or reception of lower priority messages.

2.2.4.3 Preemption

Lower priority messages shall be preempted, if necessary, to allow higher priority blocks to be transmitted and received.

Notes:

1. *For example, if a lower priority block is occupying limited HF Data Link resources when a higher priority block is received, then transmission of the lower priority block should be interrupted, if necessary and feasible, to permit transmission of the higher priority block.*

2. *The priority assigned to a data block will be determined by the initiating user or his terminal equipment.*

2.2.5 Subnetwork Installed Communications Performance (ICP)

The four ICP parameters defined in Section 1 are Delay, Integrity, Availability, and Continuity. These parameters are specified for the HF Data Link subnetwork between reference Points B and C of Figure 2-1. The data presented to Point B and Point C for transport by the HF Data Link subnetwork is defined in terms of blocks. Blocks have the characteristics of length, specified in octets, and priority level.

2.2.5.1 Transfer Delay

Transfer Delay is a measure of the time required for an information element to be transferred in one direction between the reference points B and C of Figure 2-1, on a first-bit-in to last-bit-out basis.

The Transfer Delay of a given block of data across an air/ground communications subnetwork depends on:

(a) The length, type and priority of that block and all other blocks that constitute the instantaneous user traffic loading of the subnetwork -- the **Traffic Model**.

(b) The subnetwork's throughput characteristics which are determined by its architecture, protocols, and the characteristics of its RF and Physical layer channel(s) -- the **Subnetwork Mode**l.

Notes:

1. *A number of the factors determining these characteristics are interdependent and can be different for the two directions of traffic flow (to-aircraft and from-aircraft).*

2. *It is assumed that an air/ground subnetwork's transfer delay characteristics will be established via high-fidelity simulations and/or analyses because full-scale measurements across the subnetwork under the various conditions are impracticable. The transfer delay verification procedures of Section4 utilize certain subnetwork measurements intended to validate the simulations and/or analysis.*

2.2.5.1.1 Traffic Model

The Traffic Model description shall include:

(a) a declaration of the "nominal worst case" utilization (user traffic loading) of the HF Data Link system;

(b) consideration of each factor listed below; and

(c) any additional factors having significant influence on transfer delay, which shall be identified and discussed.

The Traffic Model used for generating traffic for the subnetwork Transfer Delay characterization shall take into account the following factors:

1) discrete block inter-arrival rates

2) distribution of block lengths

3) distribution of block priority levels , and

4) the number and variety of mobile terminals active in the subnetwork

Appendix E provides the minimum acceptable Traffic Model, taking into account Items (1), (2) and (3) above. Minimum acceptable data for item (4) is not specified as this factor will be highly dependent on a number of operational variables and on the specific service(s) described by the network operator. It is expected that the values of these factors will be adjusted during simulations/analyses to establish appropriate channel loading.

Notes:

1. *The minimum model of Appendix E is applicable to certain long-range, beyond-line-of-sight aeronautical air/ground communications environments (e.g., oceanic, remote areas) and is likely to be an inadequate representation of traffic in other types of airspace for which operational approval may be desired.*

2. *It is recommended that the response to this requirement also provide information regarding the sensitivity of transfer delay performance to each factor.*

2.2.5.1.2 Subnetwork Model

The Subnetwork Model shall take account of all aspects of the subnetwork's architecture, internal protocols, management and control overhead, and the characteristics of the RF and Physical layer channel(s) that influence the transfer delay characteristics of the subnetwork.

Note: The Subnetwork Model will include the effects of overhead traffic across the RF path.

The characteristics of the RF paths and equipment's Physical Layers shall be consistent with the requirements of other sections of this document; and in particular, the nominal channel error rate determined by the analysis required by Section 3.1.1.

2.2.5.1.3 Transfer Delay Minimum Performance

For the purpose of computing transfer delay statistics, the *mean transfer delay* is the arithmetic average of the transfer delay of all blocks delivered by the system. The *95^{th} percentile* transfer delay is the 95^{th} percentile of the delivery time for all blocks submitted to the system.

*Note: These definitions are subtly different. Undelivered blocks, if any, can be viewed as an infinite delay. Undelivered blocks **are not** included in the computation of mean transfer delay. Undelivered blocks **are** included in the computation of 95^{th} percentile transfer delay.*

An HF Data Link subnetwork shall provide transfer delays not greater than the following for a standard 128 octet block.

HF Data Link Priority Level	Direction	Mean	95th Percentile
Lowest	To-aircraft	45 s	120 s
Lowest	From-aircraft	60 s	250 s
Highest	To-aircraft	45 s	90 s
Highest	From-aircraft	60 s	150 s

2.2.5.1.4 Transfer Delay Characterization of HF Data Link Subnetwork

Each HF Data Link subnetwork shall define in its associated normative attachment the transfer delay characteristics of its system for the three required safety priorities; i.e., Distress/Urgency, Flight Safety, and Other Safety. The characteristics for each priority shall be declared using of Table 2-2. The Transfer Delay Characteristics tables shall be repeated for the to-aircraft and from-aircraft directions. The transfer delay characteristics shall be determined under the "nominal worst case" loading characteristics defined by the Traffic Model. The system-specific attachment shall contain sufficient analysis, measurement, or Subnetwork Model simulation results to support the values declared in the subnetwork and traffic models.

Table 2-2: Tables for Transfer Delay Characteristics

Priority Level (e.g. Distress/Urgency, Flight Safety, Other Safety)			
Block Length	Latency	Mean	95th Percentile
(~ 10 octets)	____ s	____ s	____ s
(~ 40 octets)	____ s	____ s	____ s
128 octets	____ s	____ s	____ s
(~ 400 octets)	____ s	____ s	____ s
(~1000 octets)	____ s	____ s	____ s

Note:

1. *The latency of the HF Data Link System is defined under conditions of no user traffic loading other than the test block itself; however, normal system manage ment traffic and protocol overhead traffic are expected to be present,due to management entities internal to the subnetwork. Thus, latency is the minimum delay that can be expected within the system, and accounts for the relatively fixed delay components such as propogation delay, component transmission speeds, and latent buffering.*

2. *The mean and 95th percentile values include the common latency value.*

3. *The term "transit delay" is defined by ISO 8348 as average transfer delay, and thus is equivalent to mean transfer delay as used herein.*

4. *Values for block lengths stipulated in pro-forma Table 2-1 set off by parentheses and the symbol "~" may vary from the so-indicated values by as much as ±50%, dependent on internal system-specific constraints.*

5. *Appendix G provides guidance on the nature of transfer delays in a packet-mode network, and on methods for combining or allocating transfer delay data among serial network elements.*

6. *The requirement of Section 2.2.5.1.4 should not be interpreted as requiring different transfer delay values for each safety priority, provided that they meet the requirements of Section 2.2.5.1.3.*

2.2.5.2 Integrity

Integrity is defined as the probability that there are no undetected, HF Data Link subnetwork-induced, errors in an information block transferred across the HF Data Link sub-network, where errors include both undetected addressing errors and undetected errors in the information payload. Subnetwork integrity is independent of the data network environment in which the HF Data Link subnetwork is used.

The Integrity of a block with a length of 128 octets shall be not less than $1-10^{-6}$.

Notes:

1. *This definition of Integrity is equivalent to the value (1 - Residual Block Error Rate).*

2. *The amount of end-user data contained in each case may be quite different, due to differing proto cols that operate outside the air/ground subsystem, which may necessitate normalization of HF Data Link Integrity for combination with that of other subnetworks.*

2.2.5.3 Service Availability Criteria

A *service interruption* is defined as an event that begins whenever a data block that is presented to either Point B or Point C experiences a transfer delay in excess of the 95th percentile T_{OD} ısfer delay. A service interruption ends when a subsequent block presented at the same point experiences a delay less than or equal to the 95th percentile transfer delay.

Note: Service interruptions will occur, but will generally have no significant impact on system perfomance.Calculations of the system availability and continuity of service take into account *service interruptions whose durations exceed system-specific thresholds, as defined in Section 2.2.5.3.1 and Section 2.2.5.3.2.*

2.2.5.3.1 Service Outages

For the purposes of this standard, a Service Outage is defined as an event consisting of a service interruption (see Section 2.2.5.3) with a duration that exceeds the system-specific value T_{OD}, where T_{OD} must be less than or equal to 10 times the 95th percentile transfer delay for a 128-octet block at Distress/Urgency priority. Two values for 95th percentile transfer delay are required by Section 2.2.5.1.3, one for each direction of data transmission. The shorter of these shall be used to establish the value T_{OD}.

Notes:

1. *Operational approval of specific aircraft for HF Data Link operations will require consideration of AS failure rates and AS configurations carried onboard. For the purposes of these MASPS, the AS equipage is unknown. The methodology and assumptions of Section 3 are, therefore, based on the use of a perfect, failure-free AS.*

2. *RTCA DO-270 (AMS(R)S MASPS) divides Service Outages into two classes: Multi-User and Single-User. The architecture of the HF Data Link system makes single-user outages caused by any factor not related to on-board failure of HF Data Link avionics a negligible fraction of the total availability. Therefore, this HF Data Link MASPS considers only a single class of outage.*

2.2.5.3.2 Availability Ratio

Availability Ratio at a point in the coverage volume is defined as the ratio of actual operating time to observation time, and can be calculated as

$$Availability\ Ratio = \frac{Operating\ Time}{Observation\ Time} = \frac{Observation\ Time - Total\ Outage\ Time}{Observation\ Time}$$

For the HF Data Link System the observation time shall be real clock and calendar time; i.e., 24 hours per day, 7 days per week, 365 days per year.

When observed over a one-year interval of operation, the availability due Service Outages defined in Section 2.2.5.3.1, shall be at least 0.9. The Availability shall be computed by averaging availability ratio over all user aircraft within the each declared coverage volume.

2.2.5.4 Continuity of Service Criteria

This subsection contains continuity of service requirements for the HF Data Link subnetwork.

The HF Data Link subnetwork shall declare the actual values of the continuity of service parameters required by this subsection, and shall describe in its associated normative attachment the rationale and analyses supporting its declared continuity of service factors. Acceptable methodologies for supporting analyses are contained in normative Appendix C.

Note: Continuity of service is frequently thought about as merely a "short term availability. As discussed in Appendix C, this view is flawed and does not always give the correct interpretation

2.2.5.4.1 Continuity of Service Event

For the purposes of this document, a *Continuity of Service Event* is defined as a service interruption (see Section 2.2.5.3) with a duration that exceeds the parameter T_{SI} . The parameter T_{SI} shall be less than or equal to 10% of the continuity of service interval, T_{COS} , for 128-octet block at Distress/Urgency priority

2.2.5.4.2 Continuity of Service

Once an aircraft has committed to perform a certain operation based on the availability of the necessary communications, there must be a high probability that the communications service will continue throughout the operation without a Continuity of Service Event. This short-term probability, valid over a stated time period, is called the continuity of service.

When observed over a 15 minute continuity interval and averaged over the declared coverage volume, the Continuity of Service due to Continuity of Service Events shall be at least 0.9. The effects of user-connectivity networking among GS locations may be included in the Continuity of Service computation only if it occurs within subnetwork; i.e., between Point C and Point B.

Note: RTCA DO-270 (AMS(R)S MASPS) divides Continuity of Service events into two classes: Multi-User and Single-User. The architecture of the HF Data Link system makes single-user outages caused by any factor not related to on-board failure of HF Data Link avionics a negligible fraction of the total availability. Therefore, this HF Data Link MASPS considers only a single class of Continuity of Service Events.

2.2.6 Service Monitoring and Reporting

The HF Data Link service providers shall maintain a service monitoring, reporting and logging system.

2.2.6.1 Outage Reporting

The service provider shall declare the time necessary to detect service outages, T_{DET} , in the system-specific attachment.

Detected outages shall be reported to the affected CAA(s) within 15 minutes of detection. Predictable outages or scheduled maintenance events shall be reported to the affected CAA(s) in advance. The outage report shall be accompanied by an estimated time to service restoration.

Note: An acceptable means of monitoring are real-time monitors that issue alarms to operators if there is a failure of an element of the HF Data Link architecture.

2.2.6.2 Availability Monitoring

The HF Data Link service provider should use the observed duration of outages and the methodology of Appendix C to compute the system availability. The computation should be performed monthly using an observation time of one year, and the results should be available for CAA inspection.

2.2.6.3 Transfer Delay Monitoring

The HF Data Link service provider shall provide a mechanism to monitor transfer delay during normal operations. Transfer delay data should be presented to show the mean and 95th percentile values achieved by the system. The achieved performance should be monitored monthly using an observation time of one month, and the results should be available for CAA inspection.

2.2.6.4 Integrity Monitoring

Note: While it would be desirable to monitor integrity, the communications burden necessary to ensure the block error rates, required by Section 2.2.5.2, would consume a significant portion *of the available resources. Consequently, this MASPS does not establish an integrity monitoring requirement.*

2.2.7 Subnetwork Interoperability

Interoperability requirements assure the intended and expected functioning of the HF Data Link subnetwork in the context of an end-to-end communications system.

2.2.7.1 Subnetwork Communications Protocols

The HF Data Link subnetwork shall provide at least one communications protocol necessary to operate as a constituent subnetwork of the ATN. Either the ground equipment or the aircraft equipment, or both, may support multiple protocols, whether or not these protocols are recognized by the ATN. Safety communications shall not be compromised by the presence of multiple protocols. The HF Data Link subnetwork operating in the ATN environment with an ISO 8208 interface shall meet the requirements of RTCA DO-265 (HF Data Link MOPS).

2.2.7.2 Transparency to User Data

The HF Data Link subnetwork shall be completely transparent to user data, delivering user data to its output interface that is identical to the user data presented to its input interface, considering the integrity requirements of Section 2.2.5.2.

2.2.7.3 Interactions with Elements External to the HF Data Link Subnetwork

2.2.7.3.1 Connection Establishment Delay

When the HF Data Link subnetwork is operated with connection-oriented protocol interface, the Connection Establishment Delay at the 95th percentile shall be not greater than 256 seconds.

2.2.7.3.2 Connectivity Events

The AS and GS shall notify their respective external management entities (e.g., ATN Router) of the establishment of connectivity with the HF Data Link subnetwork through a Join Event indication, and the loss of connectivity with the HF Data Link subnetwork through a Leave Event indication. A connectivity event shall be generated within 30 seconds, at the 95th percentile, following the discovery of a change in the subnetwork's connectivity status.

2.2.7.3.3 System Control Interactions

In its system-specific attachment, the HF Data Link subnetwork shall identify and characterize all signaling and system control interactions with any external element of an end-to-end communications system. If external mobility management is necessary, details of the necessary external control interactions shall be included.

Notes:

1. *Such interactions include, but are not limited to, selection of channel, service, and service provider. It is possible that such interactions are conveyed by the communications proto col(s), details of which are disclosed in response to Section 2.2.7.1.*

2. *This information may have influence on the extent to which external connectivity-management techniques (e.g. Interdomain Routing Protocol) may be necessary.*

This page intentionally left blank.

3 SUBSYSTEM REQUIREMENT

This MASPS is generic in nature and does not establish the specific numeric values of subsystem requirements. This section describes the process of partitioning the total subnetwork requirements among the principal elements of the HF Data Link subnetwork, taking into account the institutional as well as technical interfaces. The partitioning of the subnetwork into two elements, the AS and the HF Data Link Network Infrastructure (HNI) is shown in Figure 3.1.

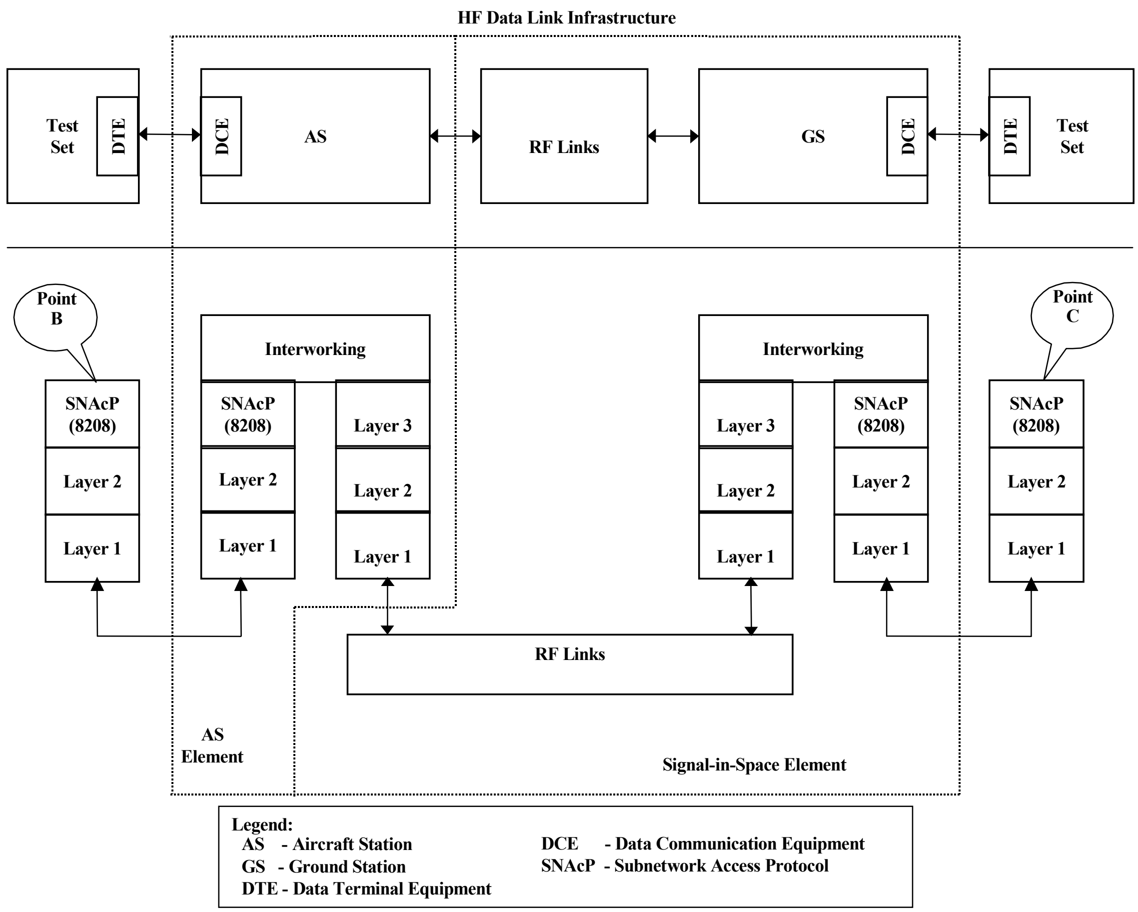


Figure 3-1: Partitioning Air-to-Ground Subnetwork into AS and HNI

This section establishes requirements for additional specific information that must be provided in the system-specific attachments and the methodology by which that information is to be provided. The purpose of this disclosure is to provide confidence that the subnetwork design will achieve the "Point B-to-Point C" performance specified in Section 2, prior to the approval of that system for HF Data Link performance. Proof of performance at the subnetwork level is achieved through the verification procedures of Section 4.

Throughout this section, the term "partitioning" is used as the term for dividing the air-to-ground subnetwork into elements that correspond to natural physical, technical and institutional boundaries. The "partitioning" methodologies prescribed in this section can be used either for "allocating" (top down) or for "aggregating" (bottom up) values of the performance parameters. To avoid unnecessary constraints on subnetwork design, this MASPS does not establish *a priori* allocations.

The partitioning assumes that failures of the AS and HNI components are independent.

3.1 Performance Partitioning Methodologies

This section describes methodologies for computing the following aspects of HF Data Link data link performance: delay, integrity, availability and continuity. The results of these computations shall be provided in the system-specific attachment.

3.1.1 RF Performance

The aeronautical HF Data Link system has been designed so that one or more HF Data Link ground stations provide overlapping coverage on a given air route using two or more frequencies. The purpose of the overlapped coverage and multiple frequency operation is to improve on the availability of a communications path over what it might be if only a single station operating on one frequency were to provide the service. Therefore an aircraft wishing to establish a link with the HF Data Link system need only establish a link with any of the HF Data Link Ground stations on any of the operating frequencies.

RF link availability is defined as the probability (or fraction of time) that the signal-to-noise ratio exceeds a minimum required signal-to-noise ratio. The minimum required signal-to-noise ratio is that which guarantees the required bit or packet error rate.

An analysis of the RF link performance of the HF Data Link is contained in Appendix B. Service providers whose system design differs in any significant way from that described in ICAO Document 9741 shall provide an analysis equivalent to that in Appendix B employing the methodology used in that appendix.

3.1.2. Transfer Delay Partitioning Methodology

Partitioning of all components of delay performance shall include the effects of internal subnetwork protocols, if any, used to ensure the integrity of the data blocks crossing the subnetwork interfaces with external subnetworks. The effects of higher level protocols implemented by Higher Level Entities external to the subnetwork shall not be included in the transfer delay calculations.

The effects of retransmission within the subnetwork (between Point B and Point C) to resolve errors in the received data shall be included in the transfer delay computations.

3.1.2.1 Latency Transfer Delay Component

The latency Transfer Delay component, t_{LAT}, shall be partitioned by means of a simple sum:

$$(t_{LAT})_{SUBNETWORK} = (t_{LAT})_{AS} + (t_{LAT})_{SIS}$$

where the subscripts indicate that the subnetwork latency is the sum of the latencies of the aircraft system (AS) and the signal-in-space (SIS) components.

3.1.2.2. Mean Transfer Delay

The mean Transfer Delay shall be partitioned among the constituent elements of the HF Data Link by means of a simple summation:

$$t_d = \mathrm{E}\{\text{delay between Point B and Point C}\}$$

$$= \sum_{\text{All HFDL Components}} (t_d)_k$$

where E{} is the statistical expected value function.

3.1.2.3 95th Percentile Transfer Delay

Partitioning of the 95th percentile Transfer Delay should be based on convolution of the Transfer Delay density functions for all elements of the link. If the detailed Transfer Delay density function for any element of the link is not available, partitioning of the 95th percentile Transfer Delay shall be performed using the methodology detailed in Appendix G. As an alternative to the process of Appendix G, the 95th percentile delay may be partitioned on a simple summation basis. System providers are cautioned that use of this alternate methodology provides an upper bound on the 95th percentile delay and may result in overly severe subsystem requirements.

Note: *Partitioning of the 95th-percentile transfer delay is a complicated mathematical exercise that requires either* a priori *knowledge of the distributions of the various elements of the transfer delay or use of simplifying assumptions.*

3.1.3 Integrity Performance

An analysis of the integrity performance of the HF Data Link is contained in Appendix D. Service providers whose system design differs in any significant way from that described in the ICAO Document 9741 shall provide an analysis equivalent to that in Appendix D employing the methodology used in that appendix.

3.1.4 Availability Methodology

The HF Data Link system-specific attachment shall provide measurement data or detailed analysis, or both, to demonstrate that the system design supports Signal-in-Space availability performance that meets the system level requirements of Section 2. This analysis shall be presented in the normative part of a system-specific attachment using the analysis methodology described in Appendix C.

The analysis of the availability shall use the following assumptions:

a) An observation time of one year (8760 operating hours).

b) The airborne antenna subsystem is part of the AS.

c) All supporting avionics and aircraft systems, for example CMU's and power systems, operate without failure.

d) HF Data Link users are dispersed uniformly throughout the declared service volume.

e) The HF Data Link user operates in a mixed environment of uniformly distributed interference sources consistent with that environment.

f) The HF Data Link avionics are enabled for communications on the HF Data Link subnetwork 100% of the time.

Note: *The effects of dual dissimilar equipage (i.e., redundant equipment for use with other dissimilar safety communications systems) are not included in the computation of availability for a specific HF Data Link system because appropriate credit for such equipage will be included in the final determination of the Installed Communications Performance for the specific aircraft installation.*

3.1.5 Continuity Methodology

The HF Data Link system shall provide a detailed analysis to demonstrate that the system design supports Continuity of Service performance that satisfies the system level requirements of Section 2.

This analysis shall be presented in the normative part of a system-specific attachment using the methodology in Appendix C.

Analysis of the Continuity shall use the following assumptions:

a) The airborne antenna subsystem is part of the AS.

b) All supporting avionics and aircraft systems, for example CMU's and power systems, operate without failure.

c) HF Data Link users are dispersed uniformly throughout the declared service area.

d) The HF Data Link user operates in a mixed environment of uniformly distributed interference sources consistent with that environment.

e) HF Data Link avionics are enabled for communications on the HF Data Link subnetwork 100% of the time.

Note: The effects of dual dissimilar equipage (i.e., redundant equipment for use with other dissimilar safety communications systems) are not included in the computation of continuity of service for the HF Data Link system. Appropriate credit for such equipage will be included in the final determination of the Installed Communications Performance for the specific aircraft installation.

3.2 AS Subsystem Requirements

The AS shall comply with the requirements of RTCA DO-265. The system-specific attachment shall utilize the minimum performance specified in the applicable MOPS when performing the analyses described in Section 3.1.

Notes:

1. *The effects of AS contributions to transfer delay are assumed to be negligible compared to the overall sub-network transfer delay.*

2. *These requirements differ from top-down systems engineering practice by assuming the existence of lower level MOPS documents prior to completion of this MASPS. While acknowledging this inconsistency, the prior publication of RTCA DO-265 makes this an appropriate practice in this particular case.*

3.3 Subnetwork Infrastructure (SNI) Requirements

3.3.1 SNI Performance Requirements

3.3.1.1. RF Link Performance Requirements

SNI RF Link Performance is partitioned in the Link Budget analysis contained in Appendix B.

3.3.1.2 Mitigation of Harmful Interference

The HF Data Link system shall be designed, characterized, implemented and managed so as to be in conformity with the interference protection requirements of the Chapter 11 SARPs; including paragraphs 11.1.1, 11.3.1.2 and 11.3.1.8 therein.

Note: 1. The Chapter 11 SARPs, in turn, make reference to ITU Radio Regulations Appendix S27.

The HF Data Link system architecture provides protection from intrasystem interference. Service providers whose system design differs in any significant way from that described in the ICAO

Document 9741 shall provide, in their system-specific attachment, an analysis showing how intrasystem interference is controlled.

Note: 2. Examples of intrasystem interference include co-channel and adjacent channel interference.

3.3.1.3 Network Coordination and Control Function

The Network Coordination and Control Function (NCCF) performs administrative and technical management functions for a HF Data Link communication system. Only those functions essential to the provision of HF Data Link need be identified.

Notes:

1. *As used in this MASPS, coordination includes the processes of intersystem coordination as described in ITU and National Radio Regulations. Coordination activities also include those additional intrasystem and intersystem processes that are necessary to support system management functions related to long-term institutional arrangements.*

2. *This Section does not require that the Network Control functions be allocated to specific subsystems (e.g., a Network Coordination Center or GS) in any particular way.*

3.3.1.3.1 Intrasystem Coordination

The system-specific attachment shall provide a description of the intrasystem coordination functions, as described in the ICAO Document 9741.

3.3.1.3.2 Intersystem Coordination

The system-specific attachment shall provide a description for the cooperative procedures for mitigating harmful interference from external systems that operate in same frequency band(s).

3.3.2 SNI Functional Requirements

The GS shall provide packet-mode interfaces with the terrestrial subsystem as shown in Figure 1-2. GS terrestrial packet-mode interfaces shall comply with an internationally recognized standard. An example of such an international standard is ISO-8208, but other standards are permissible. The system-specific attachment shall provide a full description of the interfaces.

This page intentionally left blank.

4 SUBNETWORK PERFORMANCE VERIFICATION PROCEDURES

This section provides procedures for verification that the overall subnetwork meets the requirements of Section 2. This declared performance then becomes the ICP of the subnetwork for loads up to the declared loading conditions.

The verification procedures are presented as guidelines for the measurement, analysis, simulation, and inspection methods sufficient to demonstrate compliance with the requirements. The procedures herein are defined at a high level so as to be independent of a particular system. Alternative procedures that provide equivalent compliance demonstration may be used provided that they are accompanied by documentation and justification of the methods used. The procedures cited herein may be used to evaluate the acceptability of alternative procedures for:

1. Characterizing HF Data Link packet-mode service performance at the overall air/ground subnetwork level
2. Characterizing general and other specific HF Data Link attributes and capabilities
3. Verifying that the performance, attributes and capabilities meet the HF Data Link Minimum Aviation System Performance Standards

The detailed verification procedures are contained in subsections of Section 4.2.

4.1 Verification Techniques

This document anticipates the use of four primary techniques to verify that the subnetwork performance disclosed in the system-specific attachments meets the requirements of Section 2.2. These methods include the following:

<u>Inspection</u> – In general, the following subparagraphs apply the method of inspection to every requirement listed in Section 2 that requires disclosure or discussion of specific technical details or performance analyses. This MASPS anticipates that an appropriate body, with technical expertise in HF communications systems, would review the draft system-specific attachment for technical accuracy, completeness and compliance with the requirements, methods and tables of the MASPS.

<u>Analysis</u> – The verification method of analysis is intended to be used for those performance parameters that cannot be directly measured or quantified from the operating system within a realistic time or budget. Analysis may rely on mathematical modeling and bounding techniques or may use the results of various simulation models.

<u>Modeling and Simulation</u> – As in the case of analysis, modeling and simulation results are intended to verify performance for cases that may be difficult or impossible to test in the real world. As used in this document, modeling and simulation include the use of computer modeling tools and techniques, such as ICEAREA or VOAAREA, to predict performance. The results of modeling and simulation should be validated by performance measurements, as described in the succeeding subparagraphs.

<u>Performance Measurement</u> – Actual measurement of the HF Data Link performance is the best possible verification method. Whenever the HF Data Link system operator/ service provider can present performance measurement data for conditions that match those described in this document for analysis, modeling, and simulation, such performance

measurement data is preferable and acceptable as a means of verifying compliance with a requirement of this MASPS.

4.2 Verification of Specific Requirements

4.2.1 Standard Operating Conditions

At the HF Data Link system level, the standard operating conditions shall be as established by the traffic model defined in accordance with Section 2.2.5.1.1, and the 50th percentile RF link performance as established by Appendix B. The minimum acceptable traffic model shall be as defined in Appendix E. The traffic load and composition provided in accordance with Section 2.2.5.1.1 shall be used as the basis for the analysis and simulation. Measured data, when presented as an alternative to the analysis or simulation verification detailed below, shall be related to the conditions of the traffic model.

4.2.2 Spectrum Requirements

Inspection

Verify the HF Data Link system operates in the frequency ranges identified in Section 2.2.2. Using that information, verify that ITU Radio Regulations offer appropriate protection for the declared services within such bands.

Using licensing information provided by the network operator, verify that the system has been approved as compliant with national Radio Regulations for those nations that are completely or partially contained within the declared service volume.

Analysis

None required.

Modeling and Simulation

None required.

Performance Measurement

None required.

4.2.2.1 Emissions Designators

Inspection

Inspect the relevant licensing material and verify that the emissions designator complies with the requirement.

Analysis

None required.

Modeling and Simulation

None required.

Performance Measurement

None required.

4.2.2.2 Interference

4.2.2.2.1 Emissions

Inspection

None required.

Analysis

None required.

Modeling and Simulation

None required.

Performance Measurement

The characteristics of the AS and GS designs shall be verified by means of the test procedures contained in Section 2.4 of RTCA DO-265 (HF Data Link MOPS) or other equivalent standards document

4.2.2.2.2 Undesired Signal Rejection

Inspection

None required.

Analysis

None required.

Modeling and Simulation

None required.

Performance Measurement

The characteristics of the AS and GS designs shall be verified by means of the test procedures contained in Section 2.4 of RTCA DO-265 (HF Data Link MOPS) or other equivalent standards document.

4.2.3 Coverage Volume

Inspection

Verify that the service provider declared the coverage volume.

Analysis

No additional analysis beyond that required by Section 3.1 and Appendix B is suggested.

Modeling and Simulation

Coverage is validated in Section 4.2.5.

Performance Measurement

Coverage is validated in Section 4.2.5.

4.2.4 Priority, Precedence and Preemption

Inspection

Using system-specific material provided by the network operator, verify that the system design includes provision for priority, precedence and preemption mechanisms in each of the constituent elements, and that the requirements of Section 2.2.4 and its subparagraphs are addressed.

Analysis

None suggested.

Modeling and Simulation

Starting with the simulation at a steady state based on the system traffic loading model detailed in Appendix E, simulate the effect of sufficient additional traffic to cause the priority, precedence and preemption logic to be exercised. Service requests shall be applied at both Point B (AS) and Point C (GS) of Figure 2-1. Service requests shall be presented using a exponential distribution of interarrival times, with the block size having a uniform random distribution between 128 and 1024 octets of user data. The blocks shall have a uniform random distribution among the priority levels provided by the system. The simulation shall be instrumented such that the delay time for each block can be measured and the delay statistics collected. If possible, the inner protocol layers of the simulation should be instrumented such that individual lower-priority blocks can be shown to be pre-empted in deference to higher-priority blocks. As the load on the system is increased, the statistics should show that high priority blocks are minimally delayed, and that lower priority blocks are delayed as required to ensure delivery of higher priority blocks.

Performance Measurement

The priority, precedence, and preemption characteristics of the AS design shall be verified by means of the test procedures contained in Section 2.4 of RTCA DO-265 or other equivalent standards document.

The priority, precedence, and preemption characteristics of the GS design shall be verified by means of test procedures equivalent to those contained in Section 2.4 of RTCA DO-265 or other equivalent standards document. This test is likely to utilize a multiplicity of AS's or other mobile terminals.

4.2.4.1 Priority Levels

Inspection

Using the system-specific material, verify that the system provides at least the minimum levels required by Section 2.2.4.1.

Modeling and Simulation

Covered in Section 4.2.4.

Analysis

Covered in Section 4.2.4

Modeling and Simulation

Covered in Section 4.2.4.

Performance Measurement

The test procedures of Section 4.2.4 assist in verifying this requirement. For each priority level declared in the system-specific material, create a block using an appropriate device. Using the device as an input to the AS, send the block to the ground. Verify that the GS output contains the proper block priority indicator as detailed in the system-specific material. Repeat the test in the GS-to-AS direction and confirm that the AS output contains the proper block priority indicator

4.2.4.2 Precedence

Inspection

None required.

Analysis

Covered in Section 4.2.4

Modeling and Simulation

Covered in Section 4.2.4.

Performance Measurement

Covered in Section 4.2.4.

4.2.4.3 Preemption

Inspection

None required.

Analysis

Covered in Section 4.2.4

Modeling and Simulation

Covered in Section 4.2.4.

Performance Measurement

Covered in Section 4.2.4.

4.2.5 Subnetwork Installed Communications Performance

Performance characterization denotes some combination of measurement, simulation and analysis that produces estimates of delay, integrity, availability and continuity. Measurement of delay, integrity, availability and continuity under all system conditions is not practicable and is specifically not required. If measurements are used to characterize performance, the measurements may make use of special test messages and special test hardware that may not be available in normal operations.

4.2.5.1 Transfer Delay

The objective of the transfer delay measurement test is either 1) to provide data for validation of performance declared in response to Section 2.2.5.1.4, or, 2) to validate any HF Data Link transfer delay analysis or simulation used to support the declared performance. The tests should gather sufficient delay measurements to provide statistical significance. It is important that the traffic profiles, system loading, and operational environment that prevailed during the measurements be comparable to those used in the analysis or simulation. Additional simulation runs may be required to obtain this correspondence. It is necessary to accumulate enough samples at a given channel load condition to support the development of delay Probability Density Function (PDF) and Cumulative Distribution Function (CDF) for the to-aircraft and from-aircraft directions under actual traffic conditions. (see Section 2.2.5.1)

4.2.5.1.1 Traffic Modeling

Inspection

If the declared traffic model is that defined in Appendix E, no inspection is required.

If the declared traffic model is other than that defined in Appendix E, inspect the system-specific material and verify that a description of the traffic model is included and that the description covers items (a), (b), and (c) identified in Section 2.2.5.1.1. In particular, verify that the model description covers items 1) through 4) in Section 2.2.5.1.1. Verify that a rationale is provided for the traffic levels in the traffic model being nominal worst case.

Analysis

None required.

Modeling and Simulation

None required.

Performance Measurement

None required.

4.2.5.1.2 Subnetwork Model

Inspection

Inspect the system-specific Subnetwork Model material and verify that the description covers the areas specifically identified in Section 2.2.5.1.2.

Verify that the RF Path and Physical Layer characteristics assumed by the Subnetwork Model are consistent with those declared in response to other portions of this document.

Analysis

None required.

Modeling and Simulation

None required.

Performance Measurement

None required.

4.2.5.1.3 Minimum Acceptable Transfer Delay Performance

Inspection

None required.

Analysis

None required.

Modeling and Simulation

The Subnetwork Model shall be used to simulate the Transfer Delay under the nominal worst case loading conditions defined in the Traffic Model. Using results of this simulation, verify that the transfer delay satisfies the requirements of Section 2.2.5.1.3.

Performance Measurement

None suggested. As an alternative to the verification by Modeling and Simulation, the HF Data Link transfer delay performance may be verified by measurement, provided that the measurements are related to the system loading conditions of the Traffic Model.

4.2.5.1.4 Transfer Delay Characterization

Inspection

Inspect the system-specific material and verify that the transfer delay characteristic table(s) are present and that the information is complete. Verify that the data is based on the Traffic Model(s) provided in response to Section 2.2.5.1.1. Verify that the data is supported by measurement or simulations based on the Subnetwork Model provided in response to Section 2.2.5.1.2.

Analysis

As noted in Step 4b, below.

Modeling and Simulation

As noted in Step 4b, below.

Performance Measurement

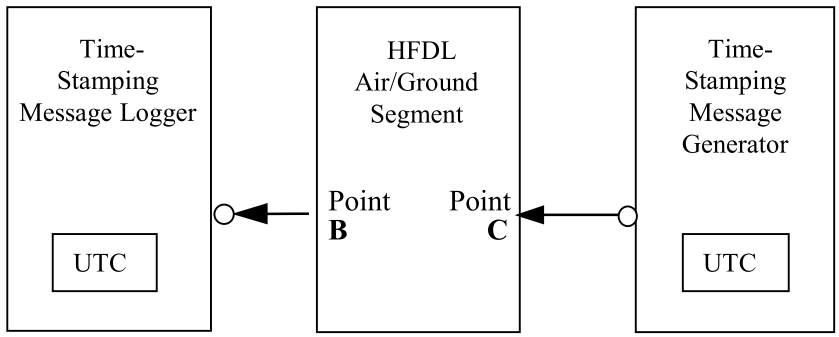
Similar test designs can be used for measurement of from-aircraft and to-aircraft one-way delay. The inaccuracy of the individual time measurements shall be no greater than ten percent of the shortest time cited in the transfer delay characteristics tables for delay for the shortest message. For the purpose of this measurement, “inaccuracy” is defined as the sum of the mean and standard deviation of the transfer delay measurement errors.

Subnetwork Model predictions of the mean and 95th percentile transfer delays of the operational system shall be verified by measurements using the following steps:

Step 1: Develop an automated HF Data Link transfer delay measurement system with capability of measuring one way transfer delays in the to-aircraft and from-aircraft directions. Figure 4-1 presents a block diagram of an acceptable measurement system for to-aircraft direction one-way transfer delay. The points B and C in Figure 4-1 correspond to the same lettered reference points in Figure 2-1.

The following are the criteria for starting and stopping the measurements of transfer delay, using the measurement points in Figure 4-1.

Direction/Event	Criterion
To-aircraft direction start event	First bit into Point C
To-aircraft direction stop event	Last bit out of Point B
From-aircraft direction start event	First bit into Point B
From-aircraft direction stop event	Last bit out of Point C



UTC = Universal Coordinated Time

Figure 4-1: Example of To-Aircraft-Direction Transfer Delay Measurement System

Step 2: For each direction and each of the 3 levels of HF Data Link priority defined in Section 2.2.4.1, send a minimum of 1000 blocks of 128 octets and record the infor mation below. For the purposes of this test procedure, each collection of at least 1000 data points is called a test.

Note: *In order to establish a practicable test, this procedure requires measurement of only a single block size from Table 2-2.*

Step 3: For each sample block:

a) Record the time of entry of the first bit of the block into the entry port,

b) Record the time of reception at the exit port of the last bit of the last block associated with the test.

c) Calculate the one way transfer time from the start and stop times.

d) Collect system loading information for the relevant subnetwork infrastructure used during each test.

Step 4: Validate that HF Data Link transfer delay simulation or analysis predictions are in statistical agreement with the measurements by the following steps.

a) For each test, run the HF Data Link simulation for the same packet length, priority, and average loading conditions and generate approximately the same number of transfer delay data points as recorded in Step 2.

b) For each test, perform an appropriate non-parametric test of the hypothesis of statistical homogeneity between the simulation samples and measured samples.

Note: A Kruskal-Wallis test is one such appropriate test.

Step 5: Verify that at least 80 percent of the tests are true at a level of significance of $\alpha = 0.05$.

4.2.5.2 Integrity

Inspection

None required.

Analysis

Analytical validation of the HF Data Link integrity is contained in Appendix D, and is based on the message structure defined in ICAO Document 9741.

Modeling and Simulation

None required.

Performance Measurement

None required.

4.2.5.3 Service Availability Criteria

Inspection

None required.

Analysis

None required.

Modeling and Simulation

None required.

Performance Measurement

None required.

4.2.5.3.1 Service Outages

Inspection

Verify that T_{OD} is declared and that it is less than or equal to 10 times the 95th percentile transfer delay in the system specific attachment.

Analysis

None required.

Modeling and Simulation

None required.

Performance Measurement

None required.

4.2.5.3.2 Availability Ratio

Inspection

None required.

Analysis

None required.

Modeling and Simulation

None required.

Performance Measurement

After the HF Data Link subnetwork has been in operation for the time required in Section 2.2.5.3.2, compliance with the requirements of Section 2.2.5.3.2 shall be verified by measured Service Outage performance collected by means of the on-going Service Monitoring characteristics of the system, as required by Section 2.2.6. Availability shall be determined by applying the methodology of Appendix C to the measured Service Outage performance.

Note: It is not the intent of the definition of Service Outage/Interruption to establish a requirement for real-time monitoring of Transfer Delay. It is anticipated that determination of Service Outages/Interruptions will be made by performance monitoring of subsystems of the subnetwork.

4.2.5.4 Continuity of Service Criteria

Inspection

Inspect the system-specific material and verify that the required values and analyses are complete. Ensure that appropriate rationale for the declared values is provided.

Analysis

None required.

Modeling and Simulation

None required.

Performance Measurement

None required.

4.2.5.4.1 Continuity of Service Events

Inspection

Inspect the system-specific material and verify that the required values for T_{SI} and T_{COS} are provided.

Analysis

None required.

Modeling and Simulation

None required.

Performance Measurement

None required.

4.2.5.4.2 Continuity of Service

Inspection

None required.

Analysis

None required.

Modeling and Simulation

None required.

Performance Measurement

Compliance with the requirements of Section 2.2.5.4.2 shall be verified by measured Continuity of Service events collected by means of the on-going Service Monitoring characteristics of the system, as required by Section 2.2.6. Continuity of Service shall be determined by applying the methodology of Appendix C to the measured performance.

4.2.6 Service Monitoring and Reporting

Inspection

Prior to approval of HF Data Link operations, inspect the technique specific material and verify that methods are described for monitoring all service volumes in which HF Data Link traffic is supported.

Analysis

None required.

Modeling and Simulation

None required.

Performance Measurement

Measurement of this requirement is accomplished in Section 4.2.6.1 through Section 4.2.6.4.

4.2.6.1 Outage Reporting

Inspection

Verify that outage detection and reporting mechanisms comply with the requirements of Section 2.2.6.1. Verify that processes exist for reporting predictable outages.

Analysis

None required.

Modeling and Simulation

None required.

Performance Measurement

After initiation of HF Data Link service, the service provider should provide, upon request, proof to CAAs of their capability to detect and report service outages to CAA Controllers within the times specified in Section 2.2.6.1. One acceptable form of proof is recorded logs of the time of service disruption, time of outage reporting to CAA, and time of service restoration.

4.2.6.2 Availability Monitoring

Inspection

None required.

Analysis

None required.

Modeling and Simulation

None required.

Performance Measurement

After initiation of HF Data Link service, the service provider should provide, upon request, proof to CAAs of their capability to generate the availability estimates.

4.2.6.3 Transfer Delay Monitoring

Inspection

Verify that transfer delay monitoring and reporting mechanisms comply with the requirements of Section 2.2.6.3. Verify that processes exist for creating the desired reports.

Analysis

None required.

Modeling and Simulation

None required.

Performance Measurement

After initiation of HF Data Link service, the service provider should provide, upon request, reports of the transfer delay performance.

4.2.6.4 Integrity Monitoring

Note: Section 2.2.6.4 contains no requirements.

Inspection

None required.

Analysis

None required.

Modeling and Simulation

None required.

Performance Measurement

None required.

4.2.7 Subnetwork Interoperability

4.2.7.1 Subnetwork Communications Protocols

Inspection

Verify that the system-specific material contains a description of the specific ATN compliance features supported by the subnetwork. If multiple interfaces are provided, verify that the details required by Section 2.2.7.1 are provided in the system-specific material.

Analysis

None required.

Modeling and Simulation

None required.

Performance Measurement

Using the appropriately configured ground (GS) and airborne (AS) assets and external ATN routers, verify that a representative sample of ATN blocks can be transmitted via the HF Data Link network between an external router on the ground and an external router in the aircraft.

If the HF Data Link subnetwork provides an ISO-8208 interface, perform the verification procedures described in RTCA DO-265, Section 2.4.19.3.

4.2.7.2 Transparency to User Data

Inspection

None required.

Analysis

None required.

Modeling and Simulation

None Required.

Performance Measurement

When performing the tests described in Section 4.2.7.1, compare the bit-stream input at Point B with the corresponding bit stream received at Point C and verify that they are identical. Repeat the collection and comparison for all blocks applied at Point C and received at Point B.

4.2.7.3 Interactions with External Elements

4.2.7.3.1 Connection Establishment Delay

Inspection

None required.

Analysis

None required.

Modeling and Simulation

None required.

Performance Measurement

With the avionics logged on to the HF Data Link system and operating in a typical operational environment, establish an air-to-ground network (e.g., ISO-8208) connection. Measure the time from the arrival of a request to establish a connection at Point B until permission to transmit on the connection is available at Point B. Follow the appropriate system-specific process to end the connection. Repeat this process a minimum of 200 times. Verify that the 95th percentile time is less than the requirement of Section 2.2.7.3.1.

Repeat this process for a ground-to-air network connection.

4.2.7.3.2 Connectivity Events

Inspection

Verify that the system-specific material identifies support for notification of Join and Leave connectivity events.

Analysis

None required.

Modeling and Simulation

None required.

Performance Measurement

On an established connection, send a block to confirm that the connection is complete. Force a disconnect. Record the elapsed time between the disconnect and the issuance of a Leave Event. Reestablish the connection. Record the elapsed time between the reestablishment of the connection and of the issuance of a Join Event.

Repeat this sequence 200 times. Verify that the 95th percentile of the elapsed times to report a Leave Event does not exceed the requirement of Section 2.2.7.3.2. Verify that the 95th percentile of the elapsed time to report a Join Event does not exceed the requirement of Section 2.2.7.3.2

4.2.7.3.3 System Control Interactions

Inspection

Verify that the system-specific material contains the information required in Section 2.2.7.3.3.

Analysis

None required.

Modeling and Simulation

None required.

Performance Measurement

None required.

4.3 Verification of Section 3 Requirements

The subsystem partitioning requirements established by Section 3 pertain to disclosure and methodology rather than subsystem performance *per se*. Therefore, as noted in Section 4.1, verifications shall be by inspection of the system-specific material for compliance with the content and requirements stated in Section 3. Where alternate methodologies are discussed in either the relevant subsection of Section 3 or the referenced Appendices, compliance with such methodologies is fully acceptable.

This page intentionally left blank.

MEMBERSHIP

Special Committee 188 High Frequency Data Link

Chairman

John Buchanan	Delta Airlines
Col. Roger Robichaux	USAF HQAMC/SCM
Robert Renoud	ARINC

Chairman Working Group 1 (MASPS)

R. Andrew Pickens	AvCom, Inc

Chairman Working Group 2 (MOPS)

George Cobley	Rockwell Collins

MASPS Drafting Group

R. Andrew Pickens	AvCom, Inc
George Cobley	Rockwell Collins
Suzanne Cullen	ARINC
Doug Feiock	ARINC
E. F. C. LaBerge	Honeywell International, Inc.
Gregory Page	ARINC

SC-188 Membership

Anton, Terri	ARINC Incorporated
Asher, Gilbert	Rockwell Collins, Inc.
Barmat, Melvin	Jansky/Barmat Telecommunications
Barros, Patrick	ARINC Incorporated
Beale, Scott	ARINC Incorporated
Bean, Joel	LB&M Associates (FAA)
Bradfield, Scott	Rannoch Corporation
Calkins, Frank	DCS Corporation
Calkins, Frank	DCS Corporation
Chang, George	1 Grp of Consultants & Independents
Clark, Mark	ARINC Incorporated
Cobley, George	Rockwell Collins, Inc.
Comeaux, Joseph	Delta Air Lines, Inc.
Cullen, Suzanne	ARINC Incorporated
Earnhardt, Neil	Rockwell Collins, Inc.
Feiock, Douglas	ARINC Incorporated
Gaffney, Brian	ARINC Incorporated
Goodman, John	TCI/BR Communications
Hasman, Frank	Federal Aviation Administration
Henry, Elbert	Federal Aviation Administration
Hess, Howard	Rockwell Collins, Inc.
Holt, Anthony	Honeywell International, Inc.
Ilarregoi, Lawrence	Convergent Sciences & Tech Corp.
Katyal, Arun	TRW, Inc.
Kellam, Paul	MITRE Corporation
Kyle, Shelle	ARINC Incorporated
LaBerge, E. F. C.	Honeywell International, Inc.
LaRocca, Phil	Federal Aviation Administration
Lebacqz, Victor	National Aeronautics & Space Administration
Mackowick, Frank	SkyComm, Inc.
Malaga, Alfonso	Honeywell International, Inc.
Nguyen, Vincent	Federal Aviation Administration
Pawlowitz, Timothy	Federal Aviation Administration

Pichavant, Claude	Airbus France
Pickens, R. Andrew	AvCom, Inc.
Renoud, Robert	ARINC Incorporated
Robinson, David	Federal Aviation Administration
Rockwell, Michael	ARINC Incorporated
Ruana, Rudolph	RTCA, Inc.
Scales, Walter	MITRE Corporation
Schlickenmaier, Herbert	National Aeronautics & Space Administration
Smith, Bernald	Soaring Society of America
Stahl, Robert	The Boeing Company
Wade, Matthew	Federal Aviation Administration
Wendel, Terence	Federal Aviation Administration

This page intentionally left blank.

Appendix A

ACRONYMS AND GLOSSARY OF TERMS

This page intentionally left blank.

APPENDIX A— LIST OF ACRONYMS AND GLOSSARY

List of Acronyms

AAC	Aeronautical Administrative Control (a class of regulated aviation radio communications)
ACARS	Aircraft Communications Addressing and Reporting System
ACP	Actual Communications Performance
ADS	Automatic Dependent Surveillance
AEEC	Airlines Electronic Engineering Committee
AMCP	Aeronautical Mobile Communications Panel
AMSS	Aeronautical Mobile-Satellite service
AM(R)S	Aeronautical Mobile (Route) Service (protected aeronautical safety communications)
AMS(R)S	Aeronautical Mobile-Satellite (Route) Service (protected aeronautical safety communications) via satellite
AOC	Aeronautical Operational Control (flight-related operator’s tasks; also, a protected class of regulated aviation radio communications)
APC	Aeronautical Public Correspondence (a class of regulated aviation radio communications)
ARINC	ARINC, inc.
AS	Aircraft Station (used in VHF and HF)
ATC	Air Traffic Control, a component of ATS
ATIS	Air Terminal Information Service
ATM	Air Traffic Management (a concept of ATC, regulatory management, operator and pilot collaboration.)
ATN	Aeronautical Telecommunication Network
ATS	Air Traffic Services (also, a protected class of regulated aeronautical radio communications
BDU	Basic Data Unit
BER	Bit Error Rate
bps	bits per second
CAA	Civil Aviation Authority
CDF	Cumulative Distribution Function
CMA	Context Management Application
CCIR	Commité Consultativ Internationale de Radio (Now ITU-R)
CCITT	Commité Consultativ Internationale des Telegraph et Telephonique (now ITU-T)
CMU	Communication Management Unit
CNS	Communications, Navigation and Surveillance (the technical cornerstones of safe flight)
CPDLC	Controller-Pilot Data Link communications
DARPS	Dynamic Aircraft Route Planning Study
Data-2	An air/ground data link interface implementation for the enveloping of external subnetwork user data with unique header identified by two octets coded as FFh

Data-3	An air/ground data link interface implementation using ISO 8208 protocol
dB	Decibel
dBm	Decibel relative to one milliwatt
DCE	Data Circuit-termination Equipment
DL	Data Link
DTE	Data Terminal Equipment
FAA	Federal Aviation Administration
FANS	Future Air Navigation System; normally associated with the ICAO FANS Committee that developed the ICAO Global CAN/ATM (FANS) Concept
FANS-1/A	Specific aircraft and ground data link system implementation
FCC	Federal Communications Commission
FCS	Frame Check Sequence
FEC	Forward Error Correction
FIS	Flight information Service, a component of ATS
FMC	Flight Management Computer
GNSS	Global Navigation Satellite System
GS	Ground station (used in VHF and HF radio)
HF	High Frequency (in aviation 2.8 – 22 MHz)
HFDL	High Frequency Data Link
HFNPDU	HF Network Protocol Data Unit
HLE	Higher Layer Entity
HNI	HF Data Link Network Infrastructure
Hz	Hertz
ICAO	International Civil Aviation Organization
ICP	Installed Communications Performance
IP	Internet Protocol
ISO	International Standards Organization
ITU	International Telecommunications Union
IWF	Internetworking Function
kHz	Kilohertz (1,000 Hertz)
km	Kilometer
LIDU	Link Interface Data Unit
LPDU	Link Protocol Data Unit
MASPS	Minimum Aviation System Performance Standard
MHz	Megahertz (1,000,000 Hertz)
MODEM	Modulator/Demodulator
MOPS	Minimum Operational Performance Standard
MPDU	Media Access Control Protocol Data Unit
ms	Millisecond (0.001 second)
MU	Management Unit
MUF	Maximum Useable Frequency
mV	Millivolt (0.001 Volt)
NAS	National Airspace Plan
NCCF	Network Coordination/Control Center Function

nmi	Nautical Mile
NOTAM	Notice to Airmen
NPDU	Network Protocol Unit
OSI	Open System Interconnect
PDF	Probability Distribution Function
PDU	Protocol Data Unit
PER	Packet Error Rate
RCP	Required Communications Performance
RCTP	Required Communications Technical Performance
RF	Radio Frequency
RNP	Required Navigation Performance
RSP	Required Surveillance Performance
RLS	Reliable Link Service
SARPs	(ICAO) Standards and Recommended Practices
SATCOM	Communications via Satellites
SC-188	RTCA Special Committee 188, High Frequency Data Link
SNAcP	SubNetwork Access Protocol
SNDCF	Subnetwork-Dependent Convergence Function (an ATN function external to the air/ground subnetwork)
SNDCP	Subnetwork-Dependent Convergence Protocol (a protocol internal to the air/ground subnetwork; which, in conjunction with an Interworking Function, translates between the SNAcP and the Link Layer)
SNI	Subnetwork Infrastructure
SNR	Signal-to-Noise Ratio
SSB	Single Side Band
SVC	Switched Virtual Circuit
TIS	Traffic Information Services (a component of ATS)
UTC	Universal Coordinated Time
VHF	Very High Frequency (in aviation, 108-137 MHz)
W	Watt

Glossary and Definitions

The following definitions of key terms used in this document are intended to be general and introductory definitions. Expansion of these terms to the precision required for quantitative purposes is done, as necessary, where the terms are used.

For the purpose of defining data performance parameters, the definitions of ISO 8348 (1987), Section 10, and ISO 8348 Addendum 1, (1987) Section 10 are incorporated herein by reference. (In defining subnetwork performance parameters, the term "network" and its abbreviation "N" in ISO 8348 and ISO 8348 Addendum 1 are replaced by the term "subnetwork" and its abbreviation "SN", respectively, wherever they appear.)

ANALYSIS – The collection and manipulation of data according to specified procedures in order to draw conclusions about behavior of a system/subsystem/component that cannot be directly observed. Simulations are included in the term “analysis”.

AIRCRAFT STATION (AS) – Consisting of an HF Data Radio or HF Data Unit used to interface between the avionics and the ground station through RF transmission.

AVAILABILITY RATIO – The probability that a system, or a specific subsystem or element, is in an operable state and capable of performing its required functions to a specified level of performance during any and all operating time.

AVAILABILITY MEASUREMENT – The result of continuous observation and recording of the set of measurable system performance parameters over a specified time interval.

BIT ERROR RATE (BER) – The probability of receiving an erroneous bit of data; the number of bit errors in an observed sample divided by the total number of bits in the sample.

BLOCK – A logically related group of information bits presented to the input of the air-ground subnetwork at either Point B or Point C. The generic term "block" is used to avoid confusion with ATN packets, subnetwork protocol units, or lower-level protocol data units.

CIRCUIT MODE – A method of data communication whereby a dedicated circuit is set up between a single user at Point B and a single ground station at Point C for the duration of information exchange, in a manner analogous to a telephone call.

CONNECTION-ORIENTED – A term used to describe the nature of the communication service provided by its interfacing protocol. A connection-oriented service, once established, appears to be a virtual circuit connection between two DTE's, and thus requires less overhead for addressing in blocks of data as compared with a connectionless service.

CONNECTIONLESS – A connectionless service is characterized by a datagram type of operation wherein the transmission network acts independently on each discrete block of data. Thus, each block must contain addressing and other information. (See Connection-oriented)
COVERAGE VOLUME – The area of the Earth's surface and correspondingly delimited airspace within which the service criteria are provided; determined by the characteristics of the subnetwork and its elements.

DATA CIRCUIT – TERMINATING EQUIPMENT (DCE) – An interface function that serves as a demarcation point of a packet-switched data network and which manages the interworking of a user's Packet-mode Data Terminal Equipment (DTE) with the network.

DATA TERMINAL EQUIPMENT (DTE) – An interface function that provides a user's application software system with a standard interworking interface to a packet-switched data network as provided by a peer Data Circuit-terminating Equipment (DCE).

END-TO-END SYSTEM – The overall system or network that provides communication services to the end users, which may be humans and/or machines. The term may also be used in referring to homogeneous elements of such a system, in which case the preferred usage is "end-to-end system".

GRADE OF SERVICE (GOS) – A measure of the probability that, during a specified period of peak traffic, a call offered to a group of circuits will fail to find an idle circuit within a specified time.

GROUND STATION (GS) – Provides connectivity between the ground networks, the transmit and receive facilities, and the AS through RF transmissions. Common components are transmitters, receivers, remote control and supervisor equipment and modems.

INTEGRITY – A measure of the absence of errors induced in a message by the system. An error is considered to include extraneous, modified, or missing information; and misdelivery. Integrity is expressed in terms of residual error probability—packet error probability in the case of packet-mode communications; bit error probability in the case of circuit-mode data communications. (See also Residual Error Probability).

INTERNETWORKING UNIT (or FUNCTION) – A system element that relates protocols accessing it to protocols exiting it. Examples of interworking units/functions are a router; a packet handler, an ISDN terminal adapter, and a translation between a Subnetwork access Protocol (SNAcP) and Subnetwork-Dependent Convergence protocol (SNDCP)

LATENCY – The average minimum delay experienced with near-zero loading of communication facilities.

LAYER – An aggregation of protocol functions in accordance with the Open System Interconnect (OSI) Reference Model. There are seven such layers, the lowest three of which are Physical (Layer 1), Data Link (Layer 2), and Network (Layer 3).

MESSAGE – A message is a quantum of information generated by a user and introduced into the system for transmission to one or more intended recipients.

MISROUTING – A result of incorrect routing actions in a subsystem or subnetwork. In this document, misrouting is used in the context of Circuit-mode services; the result of misrouting would be the connection of a call to other than the desired end terminal.

MONITORING – The observation of a system/subsystem/component during operation using equipment designed to give a direct reading of the behavior of a parameter under observation, and the recording of that reading.

NETWORK – Any combination of switches, exchanges, subnetworks or interworking units.

NETWORK CONTROL and COORDINATION FUNCTION (NCCF) – The functionality of the HF Data Link network infrastructure that performs administrative and technical management functions for the HFDL communication system.

OCTET – A unit of data consisting of eight bits.

PACKET – A unit of data sent by an end user to the system, or delivered by the system to an end user, or passed between corresponding subsystems.

PACKET MODE – A method of data communication whereby the data are transmitted in one or more discrete packets or data units, which also have a header containing addressing and network control information.

PEAK BUSY HOUR – In an observation of at least one week's duration, the one-hour period during which communications capacity demand is highest.

PEFORMANCE MEASUREMENT – The result of a discrete observation of a measurable aspect of system behavior.

PERFORMANCE VERIFICATION – The formal qualification of a network, subnetwork, system, subsystem, or any of their elements to its performance requirements. Performance can be verified by Inspection, Analysis, or Modeling and Simulation and Performance Measurement (see Section 4.0).

PRECEDENCE – The order of transmission, or access to system resources, of a message relative to other messages in accordance with defined circumstances. A common application is to order the transmission of messages queued at any given instant by their priority level and order of arrival, with the earliest and highest-priority messages receiving preference. At a particular priority level, the order of precedence is normally first-in-first-out.

PREDICTIBLE OUTAGE – An outage whose time of onset, duration and/or time of cessation can be predicted with some degree of accuracy.

PREEMPTION – An action taken by the system protocols or management mechanism to provide immediate access to system resources for certain uses. Preemption may require interruption of a message or call.

PRIORITY – An attribute of a message used to determine the order of precedence of its transmission relative to messages of other priorities, and/or the determination of the need for preemption.

PRIORITY STRUCTURE – The rank ordering of message categories, each assigned a unique priority level. When contention for limited resources exists, may be used to establish precedence or preemption actions.

RELIABILITY – In general technical terminology, reliability is an inverse measure of the frequency of failure of an entity, and can be a component of several approaches to calculating Availability of an entity.

RESIDUAL BLOCK ERROR RATE – The probability that a particular block presented to the subnetwork will be delivered from the subnetwork with undetected data or address errors. Packets lost due to error by user are not included.

SERVICE INTERRUPTION – An event during which all consecutive blocks presented to the HF Data Link subnetwork experience a transfer delay in excess of the 95th percentile transfer delay.

SERVICE OUTAGE – A service outage is defined as an interruption of service having a duration that exceeds 10 times the 95th percentile transfer delay for a 128 octet packet at Distress/Urgency priority.

SUBNETWORK – A constituent network in a chain of elements comprising an end-to-end communications link among end users, as represented in Figure 1-2.

SYSTEM – As used in this document, the total assemblage of subnetworks and subsystems providing end-to-end HFDL service to users.

SYSTEM-SPECIFIC ATTACHMENT – Documentation, provided by a service provider or system operator, in accordance with this MASPS that contains a detailed description and analysis of the subnetwork performance in the aeronautical environment.

THROUGHPUT – The rate of information transfer between two peer users of a network, subnetwork or subsystem. Throughput may be separately specified for each direction of transfer.

TRANSFER DELAY – (applicable to packet-mode services) – The elapsed time between the introduction of an identifiable quantum of information at a system input port for transmission and its appearance at the system output port, on a first-bit-in to last-bit-out basis. In ISO terms, data transfer delay is the standard speed of service parameter for the transfer of single data units. Transit delay is the average value of transfer delay.

UNDETECTED PACKET ERROR RATE – The probability that a packet delivered by the system or subsystem contains one or more erroneous data bits as compared with the data presented to the system. This is one component of residual packet error probability. In practice, higher protocol layers external to the system can be employed to reduce significantly the probability of data error.

This page intentionally left blank.

Appendix B

HF DATA LINK RF LINK PERFORMANCE

This page intentionally left blank.

APPENDIX B TABLE OF CONTENTS

APPENDIX B TABLE OF TABLES

This page intentionally left blank.

Appendix B —HF Data Link RF Link Performance

B.1 Introduction and Summary

The fundamental determinant of the performance of radio communications systems, of which HF Data Link is one example, is RF link. For any radio link, the achieved signal-to-noise ratio (SNR) determines the quality of the received signal. For radio systems using digital transmission techniques, including HF Data Link, the signal quality is normally expressed in terms of bit error rate (BER) or packet error rate (PER). Both metrics are related to SNR by well-known formulations. In general, it can be shown that the bit and packet error rate are inversely proportional to the signal-to-noise ratio. In turn, the BER or PER achieved on a communications link, working in conjunction with the processing design features of the system, directly affects the Installed Communications Performance (ICP) parameters of delay and integrity. The performance margin designed into a link – that is, the difference between the actual SNR achieved under nominal conditions and the minimum required SNR – directly affects the link availability parameter, which may be a significant part of the overall system availability quantified in the ICP.

Data link availability is defined as the probability (or fraction of time) that a measure of RF link quality such as bit error rate or packet error rate is less than a maximum specified bit or packet error rate. Hence the Data link availability is more often defined as the probability that the signal-to-noise ratio exceed a minimum required signal-to-noise ratio. The minimum required signal-to-noise ratio is that which guarantees the desired bit or packet error rate.

The basic relationships of these attributes are relatively straightforward and construction of link budgets is detailed in a number of classical texts on communications engineering, such as [x] and [y]. However, the interactions of such factors as propagation anomalies of the RF path, interference and the design features of different systems can be difficult to analyze consistently. Consequently, this appendix develops detailed link budgets with supporting rationale that demonstrate the ability of the HF Data Link to satisfy its operational objectives. Furthermore, this appendix establishes a methodology for estimating the availability of the RF path, which is a key element in the estimation of overall communications availability.

B.1.1 Background – RF Link Availability for HF Data Link

When the RF link is defined as a connection between an aircraft and a particular ground station at a particular frequency, the link availability depends primarily on the signal-to-noise ratio available at that frequency and between that pair of stations. At frequencies in the HF band (3-30MHz), it also depends very strongly on the probability that the frequency be able to propagate between the two stations. In order for a HF signal to propagate for distances well beyond line-of-sight, the signal's carrier frequency must be below the maximum frequency that can be reflected by the ionosphere. This frequency, which is sometimes referred to as the maximum useable frequency (MUF), varies as a function of range, time of day, season, geographic location, sunspot activity, and magnetic field activity. When the HF signal's carrier frequency is below the maximum useable frequency (MUF), the signal received after propagation over the HF medium suffers from multipath distortion and its amplitude fades up and down. Multipath and fading are both caused by the existence of multiple propagation paths between transmitter and receiver. Thus, the HF link availability also depends on the short term fading statistics of the HF signal and the multipath characteristics of the channel.

Methods for calculating and predicting the RF link availability for a single pair of stations and at a single frequency that take into account the signal-to-noise ratio variations and frequency 'support' have been previously developed. The best known is the "Ionospheric Communication Analysis and Prediction" (IONCAP) program [3]. IONCAP predicts the fraction of days in the month during which the available signal-to-noise ratio should exceed the required signal-to-noise ratio. The availability prediction is based on models of the ionosphere and worldwide maps of various ionospheric parameters. IONCAP requires that the geographic location of a pair of stations, the frequency, time-of-day, month, sunspot number, transmitter power and required signal-to-noise ratio be provided as inputs. IONCAP refers to this predicted number as the 'circuit reliability' or 'time availability'. Other computer programs based on the IONCAP ionospheric models also predict availability. ICECAP improves on the predictions at polar latitudes while VOACAP emphasizes on predicting the ground station's coverage area where the signal-to-noise ratio exceeds the minimum required signal-to-noise ratio.

B.1.2 HFDL link availability – An Overview

The aeronautical HF Data Link (HFDL) system has been designed so that one or more HFDL ground stations provide overlapping coverage on a given air route using two or more frequencies. The purpose of the overlapped coverage and multiple frequency operation is to improve on the availability of a communications path over what it might be if only a single station operating on one frequency were to provide service. Therefore an aircraft wishing to establish a link with the HFDL system need only establish a link with any of the HFDL ground stations on any of the operating frequencies.

Hence, the main purpose of this Appendix to is to extend the methodology used in IONCAP to compute RF link availability to include the 'ground station diversity' and 'frequency diversity' designed into the aeronautical HFDL system. A second aim is to define the relationship between HFDL link availability and signal-to-noise ratio (Link Budget) calculations and to present some results based on them.

B.2 Frequency and Path Diversity Models

Unlike other communications channels, availability of an HF link cannot be guaranteed by providing sufficient margins in link power budget to allow for the long term variations in the received signal level as well as the external noise levels. The reason, is the dependence of HF radio wave propagation on a time-varying parameter known as the Maximum Useable Frequency (MUF). Day-to-day variations in the MUF due to ionospheric disturbances have at least as big an impact on HF communications availability as signal-to-noise ratio fluctuations. The effects of loss-of-connectivity due to fluctuations in the MUF and signal-to-noise ratio are mitigated in the HFDL System specified herein for aeronautical use by providing frequency and path diversity in the network. Frequency diversity is provided by operating each HFDL ground station on two or more HF frequencies at all times. The frequencies are changed diurnally in order to cope with diurnal variations in the MUF. Path diversity is provided via deployment of HFDL ground stations that provide overlapped coverage so that when the MUF for the link to one of the ground stations falls unexpectedly, there are alternate paths with undisturbed MUFs. Extensive measurements to determine the impact of frequency and path diversity are reported in [8]. These measurements confirm that HF communications unavailability is reduced by two orders of magnitude when 4 stations provide overlapped coverage in a given geographic area with each station operating on several frequencies.

B.2.1 IONCAP Availability Model

Before defining how one might go about computing the link availability for an HFDL system that exploits frequency and path diversity, it is useful to understand how IONCAP computes the link availability (i.e. "circuit reliability"). IONCAP only computes the "circuit reliability" for a pair of stations at a single frequency. IONCAP defines the "circuit reliability" as the probability that the signal-to-noise ratio exceeds the minimum signal-to-noise ratio required for the desired grade-of-service averaged over the statistics of the MUF, that is,

$$A = \Pr\{\rho > \eta\} = \int_{-\infty}^{\infty} \Pr\{\rho > \eta \mid f_m\} p_{MUF}(f_m)\ df_m \qquad \text{[B-1]}$$

where

$A =$ RFlink availability averaged over MUF statistics

$\rho =$ signal-to-noise ratio, a statistical quantity characterized by its mean, which is a function of the operating frequency and MUF, and its standard deviations

$\eta =$ minimum signal-to-noise required for a certain grade of service

$f_m =$ MUF for the link, a statistical quantity also characterized by its mean and standard deviation

IONCAP assumes that the signal-to-noise ratio, ρ, expressed in decibels has a Normal (Gaussian) distribution with mean μ and standard deviation σ. In that case, [B-1] becomes

$$\begin{aligned}
A(\eta) &= \int_{-\infty}^{\infty} \left\{ \left[\int_{\eta}^{\infty} \frac{e^{-(\rho-\mu)^2/(2\sigma^2)}}{\sqrt{2\pi}\sigma}\ d\rho \right] p_{MUF}(f_m) \right\} df_m \\
&= \int_{-\infty}^{\infty} \left\{ \left[\int_{-M(f_m,\eta)}^{\infty} \frac{e^{-t^2/2)}}{\sqrt{2\pi}}\ d\rho \right] p_{MUF}(f_m) \right\} df_m \\
&= \int_{-\infty}^{\infty} \left\{ \left[1 - \int_{M(f_m,\eta)}^{\infty} \frac{e^{-t^2/2)}}{\sqrt{2\pi}}\ d\rho \right] p_{MUF}(f_m) \right\} df_m \qquad \text{[B-2]} \\
&= \int_{-\infty}^{\infty} \left[1 - Q(M(f_m,\eta)) \right]\ p_{MUF}(f_m)\ df_m \\
&= 1 - \int_{-\infty}^{\infty} Q(M(f_m,\eta)) p_{MUF}(f_m)\ df_m
\end{aligned}$$

where

$$Q(M) = \frac{1}{\sqrt{2\pi}} \int_{M}^{\infty} e^{-\frac{t^2}{2}} dt \qquad \text{[B-3]}$$

$$M(f_m, \eta) = \frac{(\mu(f_m) - \eta)}{\sigma} \qquad \text{[B-4]}$$

$\mu(f_m) =$ mean value of the link signal-to-noise ratio, expressed in decibels, assuming MUF=f_m [B-5]

$\sigma =$ standard deviation of the link signal-to-noise ratio, expressed in decibels [B-6]

The factor $(\mu(f_m) - \eta)$ is the link fade margin available in decibels. Therefore, $M(f_m, \eta)$ is the ratio of the link fade margin to the standard deviation of the signal-to-noise ratio fluctuations for a given MUF, frequency and minimum required signal-to-noise ratio, η. *Q(h)* is the complimentary Normal probability distribution function.

IONCAP [3] assumes that the MUF also has a Normal (Gaussian) distribution with mean MUF_{50} and standard deviation σ_{muf} In that case, [B-2] becomes

$$A(\eta) = \frac{1}{\sqrt{2\pi\sigma_{MUF}^2}} \int_{-\infty}^{\infty} \left[1 - Q(M(f_m, \eta)\right] \exp\left[-\frac{(f_m - MUF_{50})^2}{2\sigma_{MUF}^2}\right] df_m \qquad \text{[B-7]}$$

The integration over the MUF distribution can only be performed numerically. To estimate the effect of the averaging over the MUF distribution, the integral in [B-7] is approximated by a summation over 5 terms, i.e.

$$A \sim 0.403\, A_1[M(MUF_{50}, \eta)] + 0.244\, \{A_1[M(MUF_{84}, \eta)] + A_1[M(MUF_{16}, \eta)]\} + 0.0545\, \{A_1[M(MUF_{98}, \eta)] + A_1[M(MUF_{02}, \eta)]\} \qquad \text{[B-8]}$$

where

$$\begin{aligned}
A_1[M(f_m, \eta)] &= 1 - Q[M(f_m, \eta)] = \text{availability when MUF value is } f_m \\
MUF_{50} &= \text{MUF exceeded 50\% of the time} \\
MUF_{84} &= MUF_{50} - \sigma_{MUF} = \text{MUF exceeded 84\% of the time} \\
MUF_{16} &= MUF_{50} + \sigma_{MUF} = \text{MUF exceeded 16\% of the time} \\
MUF_{98} &= MUF_{50} - 2\sigma_{MUF} = \text{MUF exceeded 98\% of the time} \\
MUF_{02} &= MUF_{50} + 2\sigma_{MUF} = \text{MUF exceeded 2\% of the time}
\end{aligned} \qquad \text{[B-9]}$$

Thus, according to IONCAP [3], the RF link availability ("circuit reliability" in IOCAP terms) is computed as follows:

<u>Step 1</u>: For each of the 5 values of the *MUF* defined in Eq. [B-9] do the following:

a. Calculate the mean (or median[1]), $\mu(f_m=MUF)$, and standard deviation, σ, of the signal-to-noise ratio as outlined in Section B.3.

b. Determine the minimum required signal-to-noise ratio, η, as outlined in Section B.3.4.

c. From a and b, calculate the ratio of the link fade margin to the standard deviation of signal-to-noise ratio, $M(f_m=MUF,\eta)$, according to Eq. [B-4].

d. Calculate the availability $A_1[M(f_m=MUF,\eta)]$ according to Eqs. [B-9] and [B-3].

Step: 2: Calculate the overall link availability averaged over the MUF statistics as the weighted sum of the five values $A_1[M(f_m=MUF,\eta)]$ according to Eq.[B-8]..

B.2.2 Model of HFDL Availability with Frequency Diversity

Now consider modifications to the IONCAP availability model to account for communications between the aircraft and ground on any of several frequencies. In this case, the link is unavailable when the signal-to-noise ratio at each of the frequencies is below the minimum required signal-to-noise ratio. This means the link availability may be written as

$$A = 1 - \int_{-\infty}^{\infty} \mathrm{Prob}\{\rho_{MAX} < \eta \mid f_m\}\, p_{MUF}(f_m)\ df_m \qquad \text{[B-10]}$$

where

$\rho_{MAX} = \max(\rho_1,\ \rho_2,\ ...,\ \rho_N) =$ largest of the signal-to-noise ratios

$\rho_i,\ i = 1,\ 2,\ ...,\ N,\ =$ signal-to-noise ratio at each of the N assigned frequencies, and are statistical quantities specified by their mean $\mu_i(f_m)$ and standard deviation, σ_i

$$\mathrm{Prob}\{\rho_{MAX} < \eta \mid f_m\} = \int_{-\infty}^{\eta} p(\rho_{MAX} \mid f_m)\ d\rho_{MAX},$$

$$= \int_{-\infty}^{\eta}\int_{-\infty}^{\eta}\cdots\int_{-\infty}^{\eta} p(\rho_1,\ \rho_2,\ ...,\ \rho_N \mid f_m)\ d\rho_1 d\rho_2 ... d\rho_N \qquad \text{[B-11]}$$

and $p(\rho_{MAX} \mid f_m)$ is the probability density function of ρ_{MAX} given the MUF, $p(\rho_1,\ \rho_2,\ ...,\ \rho_N \mid f_m)$ is the joint probability density function of the signal-to-noise ratios $\rho_1,\ \rho_2,\ ...,\ \rho_N$ given the MUF for the path to the ground station.

[1] Throughout this appendix, the terms *median* (i.e. the 50th percentile) and *mean* (i.e. the statistical expected value) are used interchangeably. Athough not correct in general, this interchangeability is appropriate in this case because of the assumptions that all random variables are distributed according to Gaussian or multi-variate Gaussian probability density functions. Users are reminded and cautioned that this interchangability may not be appropriate for different choice of probability density function.

As in IONCAP, the statistics of the signal-to-noise ratio at each frequency may be assumed to be Gaussian distributed with mean $\mu_i(f_m)$ in decibels and standard deviation σ_i in decibels. In addition, some assumptions must be made about the correlation of the fading between the ith and jth signal-to-noise ratios.

If the long-term variations in signal-to-noise ratio are caused mainly by 'short-wave fading' effects, then the signal-to-noise ratio for each frequency will either increase or decrease at the same time (correlated fading). This is because all frequencies are reflected from the same general region of the ionosphere that is affected by the 'short-wave fading'. This is a worst case assumption. In this case, the integrals in Eq. [B-11] reduce to

$$\text{Prob}\{\rho_{MAX} < \eta \mid f_m\} = Q(M(f_m,\eta)) \qquad \text{[B-12]}$$

$$\begin{aligned} A &= 1 - \int_{-\infty}^{\infty} Q(M(f_m,\eta))\, p_{MUF}(f_m)\; df_m \\ &= \int_{-\infty}^{\infty} \left[1 - Q(M(f_m,\eta))\right] p_{MUF}(f_m)\; df_m \end{aligned} \qquad \text{[B-13]}$$

where

$$\begin{aligned} &M(f_m \eta) = \max\{M_1(f_m,\eta),\;\; M_2(f_m,\eta),\;\; \ldots,\; M_N(f_m,\eta)\} \\ &M_i(f_m,\eta) = \frac{(\mu_i(f_m)\text{-}\eta)}{\sigma_\iota},\ \text{for } i\ =\ 1,\ 2,\ \ldots,\ N. \end{aligned} \qquad \text{[B-14]}$$

The result in equation [B-13] is the same as the IONCAP case in [B-7] except for the definition of $M(f_m,\eta)$ which is defined as the largest of the N normalized link fade margins, $M_i(f_m,\eta)$.

Then the effects of the MUF variations are determined assuming the MUF is Gaussian distributed, as before. In that case, we get the result that the HF link availability for a pair of stations with N frequency diversity is given by Eq, [B-8] through [B-9] with $M(f_m,\eta)$ defined by Eqs.[B-14]..

To summarize this process, the RF Link Availability for a link between an aircraft and a single HFDL ground station that operates on N frequencies simultaneously is computed as follows:

Step 1: For each of the 5 values of the *MUF* defined in Eq. [B-9] do the following:

a. Calculate the mean (or median), $\mu_\iota(f_m{=}MUF)$, and standard deviation, σ_i, of the signal-to-noise ratio for each of the N frequencies as outlined in Section B.3.

b. Determine the minimum required signal-to-noise ratio, η, as outlined in Section B.3.4.

c. From a and b, calculate the normalized link fade margin, $M_i(f_m=MUF,\eta)$, at each of the N frequencies according to Eq. [B-14].

d. Select the largest normalized link margin according to Eq. [B-14], and use it to calculate the availability $A_1[M(f_m=MUF,\eta)]$ according to Eq. [B-9].. Note that for each value of the MUF, the largest normalized link fade margin may correspond to a different frequency.

Step: 2: Calculate the HFDL RF link availability averaged over 5 values of the MUF as the weighted sum of the five values $A_1[M(f_m=MUF,\eta)]$ according to Eq.[B-8].

B.2.3 Model of HFDL Availability with Path and Frequency Diversity

The next step, which comprises the main contribution of this appendix, is to extend the availability calculation to include the effects of path diversity. The simplest case of path diversity occurs when an aircraft has the freedom to communicate via either of two ground stations, each of which is operating on two or more frequencies. In this case, the link is unavailable when the signal-to-noise ratio at each frequency for each of the two ground stations is below the minimum required signal-to-noise ratio. This means the link availability may be written as

$$A = 1 - \int_{-\infty}^{\infty}\int_{\infty}^{\infty} \text{Prob}\left\{\rho_{1,MAX} \cap \rho_{2,MAX} < \eta \mid f_{m1}, f_{m2}\right\} p_{MUF}(f_{m1}, f_{m2})\ df_{m1}\ df_{m2} \qquad \text{[B-15]}$$

where

$$\begin{aligned}
&\rho_{1,MAX} = \max(\rho_{11},\ \rho_{12},\ ...,\ \rho_{1N}) = \text{largest of the station 1signal-to-noise ratios}\\
&\rho_{2,MAX} = \max(\rho_{21},\ \rho_{22},\ ...,\ \rho_{2N}) = \text{largest of the station 1signal-to-noise ratios}\\
&\rho_{ki},\ i = 1,\ 2,\ ...,\ N;\ k = 1,\ 2, = \text{signal-to-noise ratio at each of the } N \text{ assigned frequencies,} \qquad \text{[B-16]}\\
&\quad \text{assigned to station } k, \text{and are statistical quantities specified by their}\\
&\quad \text{mean } \mu_{ki}(f_m) \text{ and standard deviation, } \sigma_{ki}
\end{aligned}$$

Now following the IONCAP derivation, but considering both stations, i.e., $k = 1,\ 2$,

$$\begin{aligned}
&\text{Prob}\left\{\rho_{MAX} < \eta \mid f_{m1}, f_{m2}\right\} = \int_{-\infty}^{\eta} p(\rho_{MAX} \mid f_{m1}, f_{m2})\ d\rho_{MAX},\\
&\quad = \int_{-\infty}^{\eta}\int_{-\infty}^{\eta}\cdots\int_{-\infty}^{\eta} p(\rho_{11},\ \rho_{12},\ ...,\ \rho_{kN} \mid f_{m1}, f_{m2})\ d\rho_{11} d\rho_{12} ... d\rho_{kN}\\
&\quad \text{and } p(\rho_{MAX} \mid f_{m1}, f_{m2}) \text{ is the probability density function of } \rho_{MAX} \text{ given the } MUFs,\\
&\quad \text{from the two stations, } f_{m1} \text{ and } f_{m2},\\
&p(\rho_{11},\ \rho_{12},\ ...,\ \rho_{2N} \mid f_{1m}, f_{m2}) \text{ is the joint probability density function of the}\\
&\qquad \text{signal-to-noise ratios } \rho_{ki},\ i = 1,\ 2,\ ...,\ N;\ k = 1,\ 2, \text{ given the MUFs for the path}\\
&\qquad \text{to the } k-th \text{ ground station.}
\end{aligned}$$

[B-17]

In order to evaluate [B-17] some assumptions need to be made about the joint pdf for the signal-to-noise ratios.

As in the non-path diversity case, we assume that the variations of the signal-to-noise ratios for the path to/from ground station 1 are completely correlated. Similarly, the variations of the signal-to-noise ratios for the path to/from ground station 2 are also assumed to be completely correlated. This is a worst-case assumption.

However the signals to/from ground station 1 are reflected from a different region of the ionosphere than the signals to/from ground station 2. Hence, it is reasonable to assume that the signal-to-noise ratio variations for path 1 are de-correlated from the signal-to-noise ratio variations for path 2. Assuming normally distributed variations, Eq. [B-17] becomes

$$\text{Prob}\{\rho_{MAX} < \eta \mid f_{m1}, f_{m2}\} = L[M_1(f_{m1},\eta), M_2(f_{m2},\eta), r_{12}] \qquad \text{[B-18]}$$

where $L[M_1,M_2,r]$ is the error function associated with a bivariate Normal distribution function [9],

$$L[M_1, M_2, r] = \frac{1}{2\pi\sqrt{1-r^2}} \int_{M_1}^{\infty}\int_{M_2}^{\infty} \exp\left\{-\left[\frac{x^2 - 2rxy + y^2}{2(1-r^2)}\right]\right\} dx\, dy \qquad \text{[B-19]}$$

and

$$\begin{aligned} M_1(f_{m1},\eta) &= \max\left(M_{11}(f_{m1},\eta),\ M_{12}(f_{m1},\eta),\ \ldots,\ M_{1N}(f_{m1},\eta)\right) \\ M_2(f_{m2},\eta) &= \max\left(M_{21}(f_{m2},\eta),\ M_{22}(f_{m2},\eta),\ \ldots,\ M_{2N}(f_{m2},\eta)\right) \\ M_{1k}(f_{m1},\eta) &= \frac{\mu_{1k}(f_{m1}) - \eta}{\sigma_{1k}},\ k = 1,\ 2,\ \ldots,\ N \\ M_{2k}(f_{m1},\eta) &= \frac{\mu_{2k}(f_{m2}) - \eta}{\sigma_{2k}},\ k = 1,\ 2,\ \ldots,\ N \end{aligned} \qquad \text{[B-20]}$$

Note that $M_1(f_{m1},\eta)$ and $M_2(f_{m2},\eta)$ are the maximum normalized link fade margins for path 1 and 2, respectively, given the MUF for path 1 and path 2.

The parameter r_{12} is a measure of the correlation between the signal-to-noise ratio fluctuations on path 1 and path 2. A value of 1 indicates complete correlation and a value of 0 indicates complete de-correlation.

Substitution of Eq. [B-18] into Eq. [B-15] for the two-path availability yields

$$\begin{aligned} A &= 1 - \int_{-\infty}^{\infty}\int_{-\infty}^{\infty} L[M_1(f_{m1},\eta), M_2(f_{m2},\eta), r_{12}]\, p_{MUF}(f_{m1}, f_{m2})\ df_{m1}\ df_{m2} \\ &= \int_{-\infty}^{\infty}\int_{-\infty}^{\infty} \left[1 - L[M_1(f_{m1},\eta), M_2(f_{m2},\eta), r_{12}]\right] p_{MUF}(f_{m1}, f_{m2})\ df_{m1}\ df_{m2} \end{aligned} \qquad \text{[B-21]}$$

The function

$$A_{12}\left[M_1(f_{m1}), M_2(f_{m2}), r_{12}\right] = 1 - L[M_1(f_{m1}), M_2(f_{m2}), r_{12}] \qquad \text{[B-22]}$$

represents the RF link availability for particular values of the MUF for path 1, f_{m1}, and the MUF for path 2, f_{m1}, given the correlation between the path 1 and path 2 signal-to-noise ratio fluctuations, r_{12}. Thus, this function measures how effectively path diversity combats the signal-to-noise ratio variations due to 'short-wave fades'.

If the signal-to-noise ratio variations of path 1 are completely de-correlated with the variations of path 2 ($r_{12} = 0$), Eq. [B-22] becomes

$$A_{12}\left[M_1(f_{m1}), M_2(f_{m2}), r_{12}\right] = 1 - Q(M_1(f_{m1}))Q(M_2(f_{m2})) \qquad \text{[B-23]}$$

where $Q(M)$ is the complimentary Normal distribution function previously defined in Eq. [B-3].

On the other hand, if the signal-to-noise ratio variations of path 1 are completely correlated with the variations of path 2 ($r_{12} = 1$), Eq. [B-22] becomes

$$A_{12}\left[M_1(f_{m1}), M_2(f_{m2}), r_{12}\right] = \begin{cases} 1 - Q[M_1(f_{m1})] & \text{if } M_1(f_{m1},\eta) \geq M_2(f_{m2},\eta) \\ 1 - Q[M_2(f_{m2})] & \text{if } M_1(f_{m1},\eta) < M_2(f_{m2},\eta) \end{cases} \qquad \text{[B-24]}$$

To determine how effectively path diversity combats MUF variations, we must evaluate Eq. [B-21]. If we assume that the MUF for paths 1 and 2 have jointly Gaussian probability density function with means $MUF1_{50}$ and $MUF2_{50}$, standard deviations σ_{MUF1} and σ_{MUF1}*and* the correlation between the MUFs is r_{MUF}, then

$$p_{MUF}(f_{m1}, f_{m2}) = \left(\frac{ e^{-\left[\frac{1}{2(1-r_{MUF})^2} \left(\frac{(f_{m1}-MUF1_{50})^2}{\sigma^2_{MUF1}} - \frac{r_{MUF}(f_{m1}-MUF1_{50})(f_{m2}-MUF2_{50})}{\sigma_{MUF1}\sigma_{MUF2}} \right) + \frac{(f_{m2}-MUF2_{50})^2}{\sigma^2_{MUF2}} \right]} }{ 2\pi(1-r_{MUF})^2 \sigma_{MUF1}\sigma_{MUF2} } \right) \qquad \text{[B-25]}$$

Substitution of [B-25] and [B-22] into [B-21]yields the link availability for dual path diversity paths. This integration can only be performed numerically.

First-order approximations for some special cases may be obtained as summations of 15 to 21 terms. To explore those cases let us define the following values for MUF1 and MUF2:

$$\begin{aligned} MUF1_{50} &= \text{Path 1MUF exceeded 50\% of the time} \\ MUF1_{84} &= MUF1_{50} - \sigma_{MUF} = \text{Path 1 MUF exceeded 84\% of the time} \\ MUF1_{16} &= MUF1_{50} + \sigma_{MUF} = \text{Path 1 MUF exceeded 16\% of the time} \\ MUF1_{98} &= MUF1_{50} - 2\sigma_{MUF} = \text{Path 1 MUF exceeded 98\% of the time} \\ MUF1_{02} &= MUF1_{50} + 2\sigma_{MUF} = \text{Path 1 MUF exceeded 2\% of the time} \end{aligned} \qquad \text{[B-26]}$$

$$\begin{aligned} MUF2_{50} &= \text{Path 2 MUF exceeded 50\% of the time} \\ MUF2_{84} &= MUF2_{50} - \sigma_{MUF} = \text{Path 2 MUF exceeded 84\% of the time} \\ MUF2_{16} &= MUF2_{50} + \sigma_{MUF} = \text{Path 2 MUF exceeded 16\% of the time} \\ MUF2_{98} &= MUF2_{50} - 2\sigma_{MUF} = \text{Path 2 MUF exceeded 98\% of the time} \\ MUF2_{02} &= MUF2_{50} + 2\sigma_{MUF} = \text{Path 2 MUF exceeded 2\% of the time} \end{aligned} \qquad \text{[B-27]}$$

If the variations of *MUF1* and *MUF2* are completely de-correlated, i.e. $r_{MUF}=0$, the RF link availability is approximately equal to the following 21 term summation

$$
\begin{aligned}
A(\eta \mid r_{MUF} = 0) \approx\ & 0.16 \times A_{12}[M_1(MUF1_{50},\eta), M_2(MUF2_{50},\eta), r_{12})] \\
&+ 0.10 \times \{A_{12}[M_1(MUF1_{50},\eta), M_2(MUF2_{16},\eta), r_{12})] + A_{12}[M_1(MUF1_{50},\eta), M_2(MUF2_{84},\eta), r_{12})] \\
&\quad + A_{12}[M_1(MUF1_{16},\eta), M_2(MUF2_{50},\eta), r_{12})] + A_{12}[M_1(MUF1_{84},\eta), M_2(MUF2_{50},\eta), r_{12})]\} \\
&+ 0.06 \times \{A_{12}[M_1(MUF1_{16},\eta), M_2(MUF2_{16},\eta), r_{12})] + A_{12}[M_1(MUF1_{84},\eta), M_2(MUF2_{84},\eta), r_{12})] \\
&\quad + A_{12}[M_1(MUF1_{16},\eta), M_2(MUF2_{84},\eta), r_{12})] + A_{12}[M_1(MUF1_{84},\eta), M_2(MUF2_{16},\eta), r_{12})]\} \\
&+ 0.022 \times \{A_{12}[M_1(MUF1_{50},\eta), M_2(MUF2_{02},\eta), r_{12})] + A_{12}[M_1(MUF1_{50},\eta), M_2(MUF2_{98},\eta), r_{12})] \\
&\quad + A_{12}[M_1(MUF1_{02},\eta), M_2(MUF2_{50},\eta), r_{12})] + A_{12}[M_1(MUF1_{98},\eta), M_2(MUF2_{50},\eta), r_{12})]\} \\
&+ 0.013 \times \{A_{12}[M_1(MUF1_{16},\eta), M_2(MUF2_{02},\eta), r_{12})] + A_{12}[M_1(MUF1_{84},\eta), M_2(MUF2_{02},\eta), r_{12})] \\
&\quad + A_{12}[M1(MUF1_{02},\eta), M_2(MUF2_{16},\eta), r_{12})] + A_{12}[M_1(MUF1_{98},\eta), M_2(MUF2_{16},\eta), r_{12})] \\
&\quad + A_{12}[M_1(MUF1_{02},\eta), M_2(MUF2_{84},\eta), r_{12})] + A_{12}[M_1(MUF1_{98},\eta), M_2(MUF2_{84},\eta), r_{12})] \\
&\quad + A_{12}[M_1(MUF1_{16},\eta), M_2(MUF2_{98},\eta), r_{12})] + A_{12}[M_1(MUF1_{84},\eta), M_2(MUF2_{98},\eta), r_{12})]\}
\end{aligned}
\tag{B-28}
$$

If the variations of *MUF1* and *MUF2* are partially de-correlated, e.g. $r_{MUF}=0.707$, the RF link availability is approximately equal to the following 15 term summation

$$
\begin{aligned}
A(\eta \mid r_{MUF} = 0.707) \approx\ & 0.22 \times A_{12}[M_1(MUF1_{50},\eta), M_2(MUF2_{50},\eta), r_{12})] \\
&+ 0.08 \times \{A_{12}[M_1(MUF1_{50},\eta), M_2(MUF2_{16},\eta), r_{12})] + A_{12}[M_1(MUF1_{50},\eta), M_2(MUF2_{84},\eta), r_{12})] \\
&\quad + A_{12}[M_1(MUF1_{16},\eta), M_2(MUF2_{50},\eta), r_{12})] + A_{12}[M_1(MUF1_{84},\eta), M_2(MUF2_{50},\eta), r_{12})]\} \\
&+ 0.12 \times \{A_{12}[M_1(MUF1_{16},\eta), M_2(MUF2_{16},\eta), r_{12})] + A_{12}[M_1(MUF1_{84},\eta), M_2(MUF2_{84},\eta), r_{12}]\} \\
&+ 0.03 \times \{A_{12}[M_1(MUF1_{50},\eta), M_2(MUF2_{02},\eta), r_{12})] + A_{12}[M_1(MUF1_{50},\eta), M_2(MUF2_{98},\eta), r_{12})] \\
&\quad + A_{12}[M_1(MUF1_{02},\eta), M_2(MUF2_{50},\eta), r_{12})] + A_{12}[M_1(MUF1_{98},\eta), M_2(MUF2_{50},\eta), r_{12})]\} \\
&+ 0.025 \times \{A_{12}[M_1(MUF1_{16},\eta), M_2(MUF2_{02},\eta), r_{12})] + A_{12}[M_1(MUF1_{84},\eta), M_2(MUF2_{98},\eta), r_{12}) \\
&\quad + A_{12}[M1(MUF1_{02},\eta), M_2(MUF2_{16},\eta), r_{12})] + A_{12}[M_1(MUF1_{98},\eta), M_2(MUF2_{84},\eta), r_{12})]\}
\end{aligned}
\tag{B-29}
$$

If the variations of *MUF1* and *MUF2* are completely correlated, i.e. $r_{MUF} = 1$, the RF link availability is approximately equal to the following 5 term summation

$$A(\eta \mid r_{MUF} = 0) \approx 0.403 \times A_{12}[M_1(MUF1_{50},\eta), M_2(MUF2_{50},\eta), r_{12})]$$

$$+\ 0.244 \times \{A_{12}[M_1(MUF1_{16},\eta), M_2(MUF2_{16},\eta), r_{12})]\ +\ A_{12}[M_1(MUF1_{84},\eta), M_2(MUF2_{84},\eta), r_{12}]\} \quad \text{[B-30]}$$

$$+\ 0.0545 \times \{A_{12}[M_1(MUF1_{02},\eta), M_2(MUF2_{02},\eta), r_{12})]\ +\ A_{12}[M_1(MUF1_{98},\eta), M_2(MUF2_{98},\eta), r_{12})]\}$$

Summarizing, the RF link availability between an aircraft and either of a pair of HFDL ground stations, each of which operates on *N* frequencies simultaneously, is computed as follows:

Step 1: For each of the 5 values of the *MUF1* for the path between aircraft and ground station 1 defined in Eq. [B-26], do the following:

a. Calculate the mean (or median), $\mu_{1\iota}(f_{m1}=MUF1)$, and standard deviation, σ_{1i}, of the signal-to-noise ratio for each of the *N* operating frequencies at ground station 1 as outlined in Section B.3.

b. Determine the minimum required signal-to-noise ratio, η, as outlined in Section B.3.4.

c. From a and b, calculate the normalized link fade margin, $M1_i(f_{m1}=MUF1,\eta)$, at each of the *N* operating frequencies at ground station 1 according to Eq. [B-20].

d. Select the largest normalized link margin, $M1(f_{m1}=MUF1,\eta)$, according to Eq. [B-20]. Note that for each value of *MUF1*, the largest normalized link fade margin may correspond to a different frequency.

Step 2: For each of the 5 values of the MUF2 for the path between aircraft and ground station 2 defined in Eq. [B-26] and [B-27] do the following:

a. Calculate the mean (or median), $\mu_{2\iota}(f_{m2}=MUF2)$, and standard deviation, σ_{2i}, of the signal-to-noise ratio for each of the *N* operating frequencies at ground station 2 as outlined in Section B.3.

b. Determine the minimum required signal-to-noise ratio, η, as outlined in Section B.3.4.

c. From a and b, calculate the normalized link fade margin, $M2_i(f_{m2}=MUF1,\eta)$, at each of the *N* operating frequencies at ground station 2 according to Eq. [B-20].

d. Select the largest normalized link margin, $M2(f_{m2}=MUF2,\eta)$, according to Eq. [B-20]. Note that for each value of *MUF2*, the largest normalized link fade margin may correspond to a different frequency.

Step 3: For each pair of *MUF1* and *MUF2* values, use the normalized link margins $M1(f_{m1}=MUF1,\eta)$ and $M2(f_{m2}=MUF2,\eta)$ and the correlation of the variations in signal-to-noise ratios r_{12} to calculate the availability $A_{12}[M1(f_{m1},\eta),M2(f_{m2},\eta),r_{12}]$ according to Eqs. [B-22] and [B-19].

Step: 4: Calculate the HFDL RF link availability averaged over up to 21 pairs of values of the *MUF1* and *MUF2* as the weighted sum of the 21, 15 or 5 values $A_{12}[M1(f_{m1},\eta),M2(f_{m2},\eta),r_{12}]$ according to Eq.[B-28], [B-29], or [B-30] depending on whether the path 1 and path 2 MUF variations are completely de-correlated, partially de-correlated or are fully correlated.

The procedure for extending the HFDL Availability calculation to the case of more than two ground stations is straightforward and is left as an exercise for the interested reader.

B.3 Signal-to-Noise Ratio Model for HF Propagation

As shown in Section 2, the HF RF link availability is highly dependent on the median and standard deviation of the signal-to-noise ratio available at each assigned frequency and diversity path. This section outlines the calculation of these quantities. The signal-to-noise ratio calculations are based on the methods employed by IONCAP [3]. The median received signal and noise levels exhibit diurnal, seasonal and solar cycle variations. IONCAP is considered the best source for predicting these median values because it employs worldwide maps of ionospheric parameters derived from data collected over many years. The IONCAP model for the variations in signal strength about the median is rather simple and ignores the frequency and path length dependence of these variations. Hence, it can be improved on. Simplifications to the IONCAP calculations are also proposed in some instances to allow calculation of the availability using a spreadsheet.

B.3.1 Calculation of Received Signal Level

The HF Data Link received signal level depends on a number of factors and is given by

$$S(q) = P_t + G_t + G_r - L_t - L(q) \text{ dBm} \qquad \text{[B-31]}$$

where

$S(q) =$ the received signal level exceeded q% of the time
$P_t =$ the average transmitter power in dBm
$G_t =$ the transmit antenna gain in dBi
$G_r =$ the receive antenna gain in dBi
$L_t =$ the cable line loss at the transmitter in decibels
$L(q) =$ the propagation path loss in decibels not exceeded q% of the time

The propagation path loss not exceeded *q%* of the time is given by

$$L(q) = L_s + kL_a + (k-1)L_g + L_{MUF} + V(q) \text{ dB} \qquad \text{[B-32]}$$

where

L_s = the median spherical spreading (free-space) propagation loss in decibels

L_a =the median ionospheric absorption loss in decibels

L_g = the ground reflection loss in decibels

L_{MUF} = a factor which accounts for additional losses when the carrier frequency is above the MUF

k = the number of hops in the path between transmitter and receiver

The final term in [B-32], $V(q)$, is a factor which accounts for the variability in path loss about the median. This factor accounts for long-term fading effects such as those caused by 'short-wave fades' and day-to-day variations in the ionospheric absorption and 'ionospheric reflection height'. It does not account for multipath fading. Section B.3.4 addresses how multipath fading is accounted for in the RF link availability calculation. IONCAP [3] also adds a 9 dB loss to the median at all frequencies and distances and for latitudes below 45 degrees, i.e. $V(50) = 9$ dB. At higher latitudes the additional loss is as high as 23 dB (see discussion of Auroral absorption loss below). There is no justification given for the additional loss added to the median. A probable explanation is that 9 dB of this loss accounts for antenna gain and line losses. We account for antenna and line losses explicitly in Eq. [B-31] and auroral absorption losses are accounted for explicitly in Eq. [B-32]. Therefore $V(50)$ is assumed to be zero in this Appendix.

<u>Spherical Spreading Loss</u>: The spherical spreading loss, L_s, is the main contributor to the path loss and is given by [3]

$$L_s = 32.45 + 20\log_{10} P' + 20\log_{10} f \text{ dB} \qquad \text{[B-33]}$$

where

P' = the apparent (as opposed to actual) path length traveled in km

f = the carrier frequency in MHz

The apparent (also referred to as virtual) path length traveled by the HF signal depends on the electron density versus height profile of the ionosphere and the carrier frequency. Given an electron density profile, an accurate calculation of P' requires the use of 3-D computer ray tracing programs. If the effects of the Earth's magnetic field are neglected, simplified two-dimensional ray tracing may be employed. In this case, the "apparent" path length is given, from purely geometric considerations, by

$$P'^2 = 4k^2[(R+h')^2 + R^2 - 2R(R+h')\cos(\frac{D}{2kR})] \qquad \text{[B-34]}$$

where

D = the ground distance between transmitter and receiver

R = the radius of the Earth

h' = the "virtual" height of reflection

k = the number of hops traveled

The "virtual" height of reflection is a function of the electron density vs. height profile and the frequency. For a given electron density profile with maximum ionization level N_{max} at a height h_{max}, there is a maximum frequency $f_m = MUF$ which can be reflected by the ionosphere. This frequency is known as the "Classical Maximum Usable Frequency" or MUF for short. Frequencies above the MUF penetrate the ionosphere into outer space. Frequencies below the MUF are reflected by the ionosphere at a height $h < h_{MAX}$. The "apparent height" of reflection h' is greater than the "true height" of reflection h.

Because the height of maximum ionization in the ionosphere is time-of-day, season, geomagnetic latitude and sunspot cycle time dependent coming up with a simple answer that applies to all situations is not possible. IONCAP [3] uses worldwide maps [10] of the critical frequency, f_oF2, of the F2 layer and of the MUF for 3000 km paths to derive the height of maximum ionization, h_mF2, of the F2 layer. Then it uses two-dimensional numerical ray tracing assuming a parabolic ionization height profile to determine the "virtual" height of reflection, h', given the frequency, f, and critical frequency, f_oF2, and height of maximum ionization, h_mF2.

Typical day time values of the "spherical spreading loss one can assume day time "virtual" height of reflection vary between 250-350 km depending on geomagnetic latitude, seasonal and sunspot activity. Nighttime values vary between 350-450 km. The variation of these heights with geomagnetic latitude, season, and sunspot cycle are about $\pm 20\%$. Day-to-day variations in the "virtual" height of reflection contribute to variations in path loss about the median. It can be seen from Eqs. [B-33] and [B-34] that the impact of these variations on the spreading loss is more significant for shorter paths than for longer paths.

<u>Ionospheric Absorption Loss</u>: The second biggest contributor to the path loss is the ionospheric absorption loss that occurs while the radio signal propagates through the lower D and E layers (60-110 km heights) of the ionosphere before and after it is reflected at the F2 layer (200–400 km heights). From the theory of the absorption of radio wave energy as it propagates through the lower layers of the ionosphere, the ionospheric absorption loss, L_a, is given by [11]

$$L_a = \frac{[k\ A(f)\ \sec(\phi_0)]}{[(f + f_H)^2 + (\frac{\nu}{2\pi})^2]} \text{ dB} \qquad \text{[B-35]}$$

where

$A(f)$ = the absorption index factor which in general is a function of the frequency of the radio signal

$f_0 = \frac{\pi}{2} - \frac{D}{2kR} - \delta_0$ = angle which the radio signal makes relative to the vertical as it propagates through the lower D layer and at incidence on the E layer

$\delta_0 = \tan^{-1}\left\{\cot(\frac{D}{2kR}) - \frac{\csc\left(\frac{D}{2kR}\right)}{(1 + h'/R)}\right\}$ = elevation angle at the transmitter and/or receiver

f = the frequency of the radio signal propagating through the ionosphere

f_H = the 'gyro' frequency which is proportional to the strength of the Earth's magnetic field (~ 1.5 MHz)

ν = the "ionospheric effective electron-ion collision frequency", a parameter that characterizes the absorption of energy as the signal propagates through the ionosphere

k = the number of hops or reflections from the ionosphere

The frequency dependence of the absorption index factor $A(f)$)is due to the fact that radio signals do not propagate through the ionosphere in straight lines and the propagation velocity is frequency dependent. However, most of the absorption loss occurs in the lower portion of the ionosphere where the deviation from straight-line propagation is very small. Thus, IONCAP [3] uses an approximation recommended in [12] derived from least-squares curve-fitting to path loss vs. frequency data. In this approximation, the absorption index is independent of frequency and the frequency dependence of the denominator in [B-35] is modified to correct for the frequency dependence of A. The resultant equation for the absorption loss is [12]

$$L_a = \frac{[k\ A\ \sec(\phi_0)]}{[(f + f_H)^{1.98} + 10.2]} \text{ dB} \qquad \text{[B-36]}$$

where the absorption index, A, is equal to

$$A = 677.2 \times \left(e^{0.8445 f_o E - 2.937} - 0.04\right) \qquad \text{[B-37]}$$

and where f_0E is the "critical" frequency of the E-layer of the ionosphere in MHz. The dependence of the absorption index on f_0E is used in IONCAP to make it easy to estimate absorption loss from f_0E maps. This relationship has been obtained empirically from absorption and f_0E data [3].

The "critical" frequency of the E-layer, f_0E, is a measure of the ionization in the lower D and E layers where absorption takes place. It is very strongly dependent on time of day, season, latitude, and solar sunspot activity. These variations are described at mid and low latitudes by [6]

$$foE(\chi, R) = \max\{\ 3.3 \times [(1 + 0.008\ R)\ \cos\ \chi]^{1/4}\ ,\ 0.2\ \}\text{ MHz} \qquad \text{[B-38]}$$

where R is the 12-month running average sunspot number and χ is the solar zenith angle which defines the time-of-day, season and latitude dependence.

From [B-38] it can be seen that during peak day time hours, f_0E ranges from 3.3 MHz during low sunspot activity years to as high as 4.1 MHz during high sunspot activity years. The day-time absorption loss at frequencies below 6 MHz is significant (tens of dB) enough to limit the usefulness of these frequencies. At mid and low latitudes, solar flares can result in enhanced ionospheric absorption loss. These effects are, to some extent, limited to the sunlit area of the globe and do not affect the entire globe at once. IONCAP [3] treats these effects statistically as a variation about the median path loss.

At night, the solar related f_0E drops below 1.0 MHz to as low as 0.2 MHz, resulting in little absorption loss. At high latitudes, however, auroral-related effects produce nighttime E-layers and significant D-layer absorption. IONCAP [3] accounts for the auroral absorption effects by adding up to 14 dB to the median path loss at latitudes between 60 and 70 degrees north. Progressively smaller amounts are added at latitudes between 40 degrees and 60 degrees and north of 70 degrees.

The IONCAP treatment of auroral absorption is flawed, however, because the additional loss is applied to all frequencies. It can be seen from Eq. [B-36]that the ionospheric absorption loss has a $\frac{1}{f^2}$ frequency dependence. Assuming that the "critical frequency" of the auroral E-layer is a good predictor of the occurrance of auroral absorption, a better way to account for auroral absorption is to use the "critical" frequency of the auroral E-layer, f_0E_a, in Eq, [B-37] as follows

$$(f_0E)_{total} = \left\{ \left[f_0E(\chi,R)^4 + e^{\left(-\frac{(Y-Y_a)^2}{2Y_s^2}\right)} \right] \left(f_0E_a\right)^4 \right\}^{0.25} \quad \text{MHz} \qquad \text{[B-39]}$$

where

Y = the geomagnetic latitude at the point of reflection from the ionosphere

Y_a = the geomagnetic latitude where maximum auroral E-layer and auroral absorption effects occur

Y_s = the half-width of the latitudes at which enhanced absorption is observed

The geomagnetic latitudes $(Y_a - Y_s)$ and $(Y_a + Y_s)$ where enhanced auroral absorption effects occur have a night-time, day-time sector dependence and a dependence on geomagnetic activity [13]. Typical values for $foEa$ in the dark sectors range from less than 2 MHz to a maximum of near 2.5 MHz during periods of quite geomagnetic activity and up to 4 MHz during periods of active geomagnetic activity [13]. The width of geomagnetic latitudes affected range from 3 to 7 degrees centered at geomagnetic latitudes around 65 degrees in the dark sector and 72 degrees in the sunlit sector.

At polar latitudes, "polar cap absorption" (PCA) events caused by solar flares produce enhanced ionization levels in the D and E regions (f_0E > 3.5 MHz) that result in loss of communications at the lower frequencies in the HF band. However, these events are limited to the regions around the magnetic pole, and are very rare during the low sunspot years and are more frequent during the high sunspot years of the solar cycle.

Ground Reflection Loss: For multi-hop propagation, the losses due to reflection of the signal by the ground also must be accounted for. To a first order approximation, the ground reflection loss, L_g, is given by

$$L_g = 10(k-1)\log_{10}\left[\frac{|R_v(\delta_0)|^2 + |R_h(\delta_0)|^2}{2}\right] \text{dB} \quad \text{[B-40]}$$

where

R_v = the ground reflection coefficient for vertically polarized waves
R_h = the ground reflection coefficient for horizontally polarized waves
δ_0 = the angle which the elevation angle of the radio signal at the point of reflection

When propagation is over sea water, the reflection coefficients are near unity, so the ground reflection loss is very small.

MUF and Over-the-MUF Loss: When the carrier frequency is above the MUF, most of the energy propagates through the ionosphere and a small fraction is reflected back towards the ground. The higher the frequency is above the MUF the less energy is reflected. IONCAP [3] uses the following approximation to calculate the over-the-MUF loss, L_{MUF}

$$L_{MUF} = -10\log_{10}\left[0.5\ \text{erfc}\left(\frac{(f - MUF)}{\sqrt{2}\sigma_f \sec\phi_0}\right)\right] \text{dB} \quad \text{[B-41]}$$

where erfc(.) is the complimentary error function, MUF is the maximum usable frequency and σ_f is a parameter which determines how fast the signal is attenuated at frequencies above the MUF $(\sigma_f = 0.1\ \text{MHz})$.

As seen in Section 2, the MUF has a significant impact on the RF link availability due to the loss factor in Eq. [B-41]. IONCAP [3] uses worldwide maps of the MUF for a 3000 km path, MUF(3000), and for the "critical frequency" of the F2 layer, f_0F2, to first estimate the height of the F2 layer, h_mF2. IONCAP then uses h_mF2 and f_0F2 and a model of the vertical ionization profile of the ionosphere to calculate the 'virtual height' of reflection, h', and the median value of the MUF for the path distance D of interest.

An approximation to the calculations performed by IONCAP which is suitable for spreadsheet calculations, may be obtained by treating the reflecting region of the ionosphere as a thin layer. In this case the MUF is approximately given by [6]

$$\text{MUF}(D) = f_0\text{F2} \times \left[\frac{\left(1 + \frac{h'}{R} - \cos(\frac{D}{kR})\right)^2 + \sin^2(\frac{D}{kR})}{\left(1 + \frac{h'}{R} - \cos(\frac{D}{kR})\right)^2}\right] \quad \text{[B-42]}$$

where

f_0F2 = "critical frequency" of the F2-layer of the ionosphere in MHz, which varies with time of day, season, sunspot number, and geomagnetic latitude

h' = height of reflection which also varies with time of day, etc.

$R = 6{,}378$ km = is the radius of the Earth

D = path length

k = number of hops or reflections from the ionosphere

Thus, given MUF(3000) and f_oF2, Eq.[B-42] can be used to estimate h' by setting D=3000 and solving for h'. The estimated value of h' can then be used to calculate MUF(D) at other ranges.

IONCAP [3] estimates the solar cycle variations in MUF(3000) and f_oF2 by interpolation of monthly median values of f_oF2 and MUF(3000) for every hour, month and for 12-month average sunspot numbers equal to 10, 110 and 160. That is,

$$f_0\mathrm{F2}(R) = f_0\mathrm{F2}(0)[1 + aR] \;,\; 0 < R < 110 \qquad \text{[B-43]}$$

$$f_0\mathrm{F2(R)} = f_0\mathrm{F2}(110))[1 + b(R - 110)] \;,\; 110 < R \qquad \text{[B-44]}$$

where

$$f_0\mathrm{F2}(0) = 1.1\, f_0\mathrm{F2}(10) - 0.1\, f_0\mathrm{F2}(110)$$

$$\mathrm{a} = \frac{0.01\,[f_0\mathrm{F2}(110) - f_0\mathrm{F2}(10)]}{\mathrm{f_0F2}(0)}$$

$$\mathrm{b} = \frac{0.02\,[f_0\mathrm{F2}(160) - f_0\mathrm{F2}(110)]}{f_0\mathrm{F2}(110)}$$

and similarly for MUF(3000). Approximate values for a and b are 0.0064 and 0.0025 [6]. Typical day-time values of f_0F2 at mid-latitudes range from 5.5 MHz during years of low sunspot activity, and up to 11-12 MHz during years of high sunspot activity. Night-time minimum values of f_0F2 at mid-latitudes range from 3 MHz during low sunspot activity years to 6 MHz during high sunspot activity years.

Variations in the Received Signal Level and MUF about their Medians: When comparing the received signal levels at the same time-of-day on two different days of the same month, there will be differences in the received signal level. These differences are due to two factors: 1) changes in the ionospheric absorption loss due to changes in the ionization levels in the D and E layers; and 2) changes in the reflection height due to changes in the ionization profile of the F2 layer.

IONCAP [3] accounts for the above effects by assuming that the signal level exceeded 90% of the time suffers an additional loss, $V(90)$, which is independent of frequency or path length. The additional loss factor $V(90)$ is, however, assumed to differ somewhat with time-of-day. Consequently, IONCAP availability predictions may be too pessimistic at some frequencies and/or path lengths and too optimistic at others. IONCAP introduces another correction factor, called the Service Probability, to compensate for the probability that the predicted medians and 90% percentile signal levels are in error. This correction factor compensates in the event that the prediction was too optimistic but it makes matters worse when the prediction is too pessimistic to begin with. Hence, we do not use it in this baseline link analysis for HF Data Link.

An alternate approach to that used by IONCAP consists of applying the same data that was used to generate the worldwide maps of median values of f_0E, f_0F2, and MUF(3000) to determine the variability (standard deviation or 90% values) of f_0E, f_0F2, and h'. The 90% values of f_0E and h' can then be used to determine $V(90)$ and $S(90)$ using the same formulas used to calculate the median $S(50)$.

The variations of the MUF about its median can also be determined from the variations in f_0F2 and h'.

B.3.2 HF Noise Level

The total system noise level, N, at the receiving antenna of an HF system is given by

$$N = 10\log_{10}\left[k(T_e + (L_r - 1)T_a + LT_r)B\right] \text{ dBm} \qquad \text{[B-45]}$$

where

κ = Boltzmann's constant = 1.38×10^{-23} watts/(K-Hz)
T_e = external noise temperature seen by the receiving antenna in Kelvins (K)
L = antenna and line losses between the antenna and the receiver
T_a = antenna and transmission line temperature in Kelvins
T_r = receiver noise temperature in Kelvins
B = receiver noise bandwidth, assumed to be 3 kHz

and where it has been assumed that the antenna and transmission line are at ambient temperature.

At frequencies in the HF band the external noise level is significantly higher than the receiver noise. There are several noise sources that contribute to the external noise: galactic noise, atmospheric noise due to lightning, and man-made noise. As it will be seen from the discussion to follow, a different noise source may predominate at different frequencies.

Galactic Noise; Galactic noise is the noise level measured in extremely quiet receiving sites and represents the minimum expected noise level. IONCAP models the frequency dependence of galactic noise as [3]

$$N_g(50) = -135 - 22\ \log_{10}\left(\frac{f}{3}\right) \text{ dBm/Hz} \qquad \text{[B-46]}$$

where $N_g(50)$ is the median galactic noise power measured in a 1 Hz bandwidth, and f is the frequency in MHz.

The galactic noise level not exceeded 90% of the time, $N_g(90)$, is 2 dB higher [3].

Atmospheric Noise: More typically, the external noise seen by the receiving system is atmospheric noise due to lightning. This noise propagates over very long distances via the same mechanism as HF signals and has a distinct geographic, diurnal, seasonal and solar cycle dependence. Worldwide maps of median atmospheric noise levels at 1 MHz and variability about the median have been published by the ITU-R (formerly CCIR) in [5]. The atmospheric noise worldwide maps are for discrete four-hour time blocks for four seasons of the year. A frequency dependence and variability (10% and 90%) accompanies the maps for each 4 hour time block. Atmospheric noise levels predominate in equatorial areas and are higher during the rainy months. At very high latitudes, atmospheric noise levels are comparable to galactic noise

Numerical coefficients which describe the geographic, and frequency dependence of atmospheric noise data published in [5] are also published in [7]. IONCAP uses these coefficients to predict the atmospheric noise level at a given time-of-day, season and geographic location. For the purpose of this work, we are more interested in the worldwide yearly median atmospheric noise level and its distribution about the median. Fortunately, such data has been derived from the ITU-R data in [5] and are reported in [4] in graphical form.

The worldwide median atmospheric noise and its frequency dependence for all times-of-day, geographic locations and seasons may be deduced from the graphical data reported in [4] and is approximately given by

$$N_a(50) = -131 - 25\ \log_{10}\left(\frac{f}{3}\right)\ \text{dBm/Hz}, 3\ \text{MHz} < f < 10\ \text{MHz} \qquad \text{[B-47]}$$

$$N_a(50) = -144 - 66\log_{10}(\frac{f}{10})\ \text{dBm/Hz},\ \ 10\ \text{MHz} < f < 30\ \text{MHz} \qquad \text{[B-48]}$$

where $N_a(50)$ is the the atmospheric noise power exceeded 50% of the locations and at all times of day and seasons measured in a 1 Hz bandwidth, and f is the frequency in MHz.

The atmospheric noise levels not exceeded in 99.5% of the locations of the Earth and at all times of day and seasons may also be deduced from the graphical data reported in [4] and are approximately given by

$$N_a(99.5) = -102 - 63\log_{10}\left(\frac{f}{3}\right)\ \text{dBm/Hz}, 3\ \text{MHz} < f < 20\ \text{MHz} \qquad \text{[B-49]}$$

$$N_a(99.5) = -154 - 110\log_{10}(\frac{f}{20})\ \text{dBm/Hz},\quad 20\ \text{MHz} < f < 30\ \text{MHz} \qquad \text{[B-50]}$$

Man-made Noise: When the receive site is not in a very quiet area the contribution of the noise from power lines, car ignition or engine noise and industrial machinery may be the limiting factor. HFDL ground stations should be located in rural areas in order to minimize the effects of man-made noise.

IONCAP uses the following frequency dependence for man-made noise levels in rural areas are given in [3]

$$N_m(50) = -118 - 29\log_{10}\left(\frac{f}{3}\right) \text{ dBm/Hz} \quad \text{[B-51]}$$

where $N_m(50)$ is the rural median man-made noise power measured in a 1 Hz bandwidth, and f is the frequency in MHz.

The man-made noise level not exceeded 90% of the time, $N_m(90)$, is taken in IONCAP to be 7 dB higher than the median [3].

Median of Total External Noise Level and Variability: To compute the total median (or mean) external noise level and its variability about the median, the contributions from galactic, atmospheric and man-made noise are summed up as follows.

The median noise levels from each source are summed up in milliWatts. That is, divide the noise levels in dBm by 10, raise 10 to this power, sum the noises, and take 10 times the log of the sum to get the median external noise level in dBm.

The 90% level (or 99% if desired) of the total external noise level is computed the same way. That is, divide the 90 percentile noise levels in dBm by 10, raise 10 to this power, sum the noises, and take 10 times the log of the sum to get the 90 percentile external noise level in dBm.

B.3.3 Interference Signal Levels

Co-channel and adjacent channel interference will affect the performance of an HF communication system. Careful spectrum planning for aeronautical users limits the co-channel interference to 15 dB below the desired signal at the edges of the coverage area, which is assumed to be 5000 km. The link budgets presented in the next section compute the minimum median signal level at a distance of 5000 km. The co-channel interference is then assumed to be 15 dB below that level throughout the coverage area.

The adjacent channel interference level will depend on the frequency separation between channel assignments within the coverage area and the proximity of the interferers. For analysis purposes a 21 dB signal-to-adjacent channel interference is assumed. Unlike the co-channel interference level, which is held constant throughout the coverage area, the adjacent channel interference level is computed with respect to the median signal level at the current range, and, therefore, changes throught the coverage volume.

The total interference level is computed by summing the co-channel and adjacent channel interference, expressed in milliwatts, and then converting the answer back to dBm.

B.3.4 Required Signal-to-Noise Ratios and Multipath Fade Margins

The discussion in Section 2 showed that the HF Data Link RF link availability depends on three factors: the signal-to-noise ratio available, the MUF, and the minimum Required Signal-to-Noise Ratio to achieve the desired grade-of-service, i.e. packet error rate.

The signal-to-noise ratios required to achieve the desired packet error rate depend on the presence or absence of channel multipath and fading, the modulation and forward error correction coding, the data rate, etc. With regards to multipath, there are two factors to consider: one is the "2-sigma" multipath spread and the other is the number of independently fading multipath components. When the "2-sigma" multipath spread of the channel exceeds the multipath protection capability designed into the receiver, the multipath causes severe inter-symbol interference resulting in poor bit or packet error rate even at high signal-to-noise ratios. However, when the "2-sigma" multipath spread is smaller than the multipath protection capability designed into the receiver, then inter-symbol interference is not a problem. In this case, the performance of the receiver depends on the number of independently fading (i.e. resolvable) multipath components. The more independently fading multipath components, the better the receiver performs. This is because the probability that all of the resolvable multipath components fade (disappear) at the same instant is much smaller when there are 3 independently fading components than when there are only two or one. Bit or packet errors occur only when all of the resolvable multipath components fade below the noise level simultaneously.

CCIR Report 549-2 [2] defines three types of multipath fading characteristics (see Table B-1) for HF channels with 3 kHz bandwidth. The CCIR report does not indicate, however, how many resolvable multipath components can be expected for each type of channel. From the channel parameters it would appear that these types of channels are of the discrete multipath reflection type that is typically encountered most of the time. The ITU-R is currently working on defining additional types of channels for severely disturbed (spread-F type) HF channels where the multipath is of the scatter type.

Table B-1: HF Channel Multipath Conditions

Channel Conditions	Differential Time Delay	2-sigma Frequency Spread
Good	0.5 ms	1 Hz
Moderate	1.0 ms	0.5 Hz
Poor	2.0 ms	1 Hz

In general, if the channel multipath is of the discrete reflection type and the channel bandwidth is 3 kHz, then the number of resolvable multipath components is equal to the number of discrete reflections with delay difference greater than 0.33 ms. Examination of the types of channels defined in Table B-1 indicates that all three types of channels have at least two resolvable multipath components.

The specifications for HF Data Link [14] require that the HFDL receivers provide up to 4 ms of multipath protection based on the channel types defined in Table B-1. Thus, a HF channel with 2 paths of equal amplitude, delay spread of 0.5 ms to 4 ms, and independent complex Gaussian fading statistics with fade rate of 1 Hz is assumed for the purpose of determining the minimum required signal-to-noise ratio. This is known as the Watterson HF channel model [1]. Using a channel model with more than two multipath fading components would only result in better performance, and hence smaller required signal-to-noise ratios and multipath fade margins

The signal-to-noise noise ratios, S/N, measured in a 3 kHz bandwidth required to achieve less than 5% packet error rate as function of the HFDL modem data rate are summarized in the table below. Two sets of numbers are given: a) S/N required to achieve less than 5% packet error rate when the only distortion is Gaussian noise (external plus receiver) plus 40 Hz carrier offset; and b) S/N required to achieve less than 5% packet error rate when the received signal is distorted by multipath (two equal level paths) with less than 4 ms delay spread, and the two paths are fading with 1 Hz fade rate (i.e. frequency spread), and the carrier frequency offset is 40 Hz. The difference between the two sets of numbers is the fade margin required cope with multipath and short-term fading. The required signal-to-noise ratios are based on measurements in a controlled environment using calibrated HF Channel multipath and fading simulators.

Table B-2: Required Signal-to-Noise Ratio

	Required Signal-to-Noise Ratio		
Modulation and User Data Rate	Gaussian Noise Channel $(S/N)_{req}$	Multipath Fading Channel $(S/N)_{req}$	Multipath Fade Margin Required
BPSK – 300 bps	- 2.5 dB	+ 5.0 dB	7.5 dB
BPSK – 600 bps	+ 0.5 dB	+ 8.0 dB	7.5 dB
QPSK – 1200 bps	+ 3.5 dB	+ 11.5 dB	8.0 dB
8PSK – 1800 bps	+ 7.5 dB	+ 16.0 dB	8.5 dB

B.4 HFDL Link Availabilty and Link Budgets

Tables B-3 and B-4 summarize the calculation of RF link availability using the approach outlined in Section 2. The tables assume day time propagation, coverage provided by two ground stations each of which is operating on two frequencies simultaneously: one in the 13 MHz band and the other in the 17.9 MHz band.

Table B-3 provides the availabilities calculated for air-to-ground communications at 1800 bps from an aircraft that is 1000 km away from ground station 1 and 5000 km away from ground station 2. Table B-4 provides similar data for an aircraft that is 5000 km away from ground station 1 and 3000 km away from ground station 2.

Table B-3 Day-Time RF Link Availability for Two-Ground Stations at 1000 and 5000 km Ranges

Prob f_m < MUF	DAY TIME Air-to-Ground Availabilities					
	RANGE 1000 km			RANGE 5000km		
		1800 bps Availability			1800 bps Availability	
	MUF (MHz)	@ 13.0 MHz	@ 17.9 MHz	MUF (MHz)	@ 13.0 MHz	@ 17.9 MHz
98 %	10.7	0.0 %	0.0 %	17.9	36.48 %	7.20 %
84 %	13.1	98.91 %	0.0 %	22.0	36.48 %	27.24 %
50 %	15.6	99.83 %	0.0 %	26.0	36.48 %	27.24 %
16 %	18.0	99.83 %	99.93 %	30.1	36.48 %	27.24 %
2 %	20.4	99.83 %	100.0 %	34.2	36.48 %	27.24 %
Availability with 1GS/1F		94.17 %	29.83 %		36.48 %	26.15 %
Availability with 1GS/2F		94.20 %			36.48 %	
Availability with 2GS/2F		96.30 %				

Table B-4 Day-Time Link Availability for Two-Ground Stations at 5000 and 3000 km Ranges

Prob f_m < MUF	DAY Air-to-Ground					
	RANGE 5000 km			RANGE 3000km		
		1800 bps Availability			1800 bps Availability	
	MUF (MHz)	@ 13.0 MHz	@ 17.9 MHz	MUF (MHz)	@ 13.0 MHz	@ 17.9 MHz
98 %	17.9	36.48 %	7.20 %	19.1	88.02 %	96.02 %
84 %	22.0	36.48 %	27.24 %	23.4	88.02 %	96.02 %

Prob f_m < MUF	DAY TIME Air-to-Ground Availabilities					
	RANGE 5000 km			RANGE 3000km		
		1800 bps Availability			1800 bps Availability	
	MUF (MHz)	@ 13.0 MHz	@ 17.9 MHz	MUF (MHz)	@ 13.0 MHz	@ 17.9 MHz
50 %	26.0	36.48 %	27.24 %	27.7	88.02 %	96.02 %
16 %	30.1	36.48 %	27.24 %	32.1	88.02 %	96.02 %
2 %	34.2	36.48 %	27.24 %	36.4	88.02 %	96.02 %
Availability with 1GS/1F		36.48 %	26.15 %		88.02 %	96.02 %
Availability with 1GS/2F		36.48 %			96.02 %	
Availability with 2GS/2F		97.47 %				

Each table lists the distribution of the MUF, i.e. Eqs.[B-26] and , for the link to each ground station. Each table also shows the single-frequency availability calculated for each value of the MUF using Eq. [B-9] and the single-frequency availability averaged over the 5 MUF values (1GS/1F) calculated using Eq. [B-8]. The link margins used in the calculation for the median MUF_{50} value are shown in Table B-5. Link margins for other values of the MUF are determined in similar fashion. Notice that when the operating frequency is above a particular MUF value, the availability is 0.0%. When the operating frequency is below a particular MUF value, the availability is higher than 50% if the signal-to-noise ratio link margin for 1800 bps operation is positive. And the availability is below 50% if the link margin is negative, as is the case at the 5000 km range.

The next to the last row of each table shows the improvement in link availability at each ground station due to the use of two operating frequencies. The entries labeled Availability 1GS/2F have been calculated using Eq. [B-8] but with the link margin calculated per Eq. [B-14]. Notice that in the case of ground station ranges equal to 3000 and 5000 km, the 1GS/2F Availability is equal to the largest of the 1GS/1F availabilities. This is because at these ranges, the same frequency (13 MHz at 5000 km range and 17.9 MHz at 3000 km range) provides better availability for all values of the MUF. However, in the case of the ground station range of 1000 km, there is an improvement in availability due to the use of two operating frequencies over what it would be if a single frequency were used. This is because the 17.9 MHz frequency provides better availability for some values of the MUF while the 13.0 MHz frequency provides better availability for others. The improvement is modest because the availability was good to begin with.

The last row of each table shows the Availability improvement due to the use of two ground stations with two frequencies each. These entries have been calculated using Eq. [B-29] which assumes that the MUFs for the two ground stations are partially de-correlated and using Eq. [B-23] which assumes that the signal-to-noise ratio variations for the two paths are de-correlated.

Tables B-5, B-6, B-7 and B-8 show several examples of link margin calculations for nominal day time and night time conditions and for selected frequencies and path lengths. The tables present the median (50%) signal-to-noise-plus-interference ratio, and 99% signal-to-noise ratio available at each of two frequencies for three different path lengths using the methods described in Section B.3. The tables also show the link margin and ratio of link margin to standard deviation of the signal-to-noise ratio available at 300, 600, 1200 and 1800 bps using the required signal-to-noise ratios defined in Section B.3.4. These quantities can then be used to calculate the single ground station and two ground station link availabilities by following the methodology outlined in Section 2.

Table B-5 Daytime Link Budget, Air-to-Ground Direction

Ground Range D (km)	1000	3000	5000	1000	3000	5000
Carrier frequency (MHz)	13.0	13.0	13.0	17.9	17.9	17.9
Time block	Day	Day	Day	Day	Day	Day
f_oE (MHz)	3.4	3.4	3.4	3.4	3.4	3.4
f_oF2 (MHz)	8.5	8.5	8.5	8.5	8.5	8.5
Reflection height h' (km)	350	350	350	350	350	350
Number of hops	1	1	2	1	1	2
Path length P' (km)	1243	3153	5315	1243	3153	5315
Elev Take-off Angle (deg)	32.0	6.0	9.6	32.0	6.0	9.6
50% MUF (MHz)	15.6	27.7	26.0	15.6	27.7	26.0
Std Deviation of MUF (MHz)	2.4	4.3	4.1	2.4	4.3	4.1
EIRP (dBm)	48	48	48	48	48	48
Spreading Loss (dB)	116.7	124.7	129.3	119.4	127.5	132.1
50% Over MUF Loss (dB)	0.0	0.0	0.0	203.0	0.0	0.0
50% Ionospheric Loss (dB)	4.6	8.3	15.5	2.6	4.7	8.8
50% Rcvd Signal Level (dBm)	-73.3	-85.0	-96.8	-277.1	-84.2	-92.9
Receive Antenna Loss (dB)	3.0	3.0	3.0	3.0	3.0	3.0
Receiver Noise Figure (dB)	25.0	25.0	25.0	25.0	25.0	25.0
50% Galactic NFig (dB)	26.0	26.0	26.0	22.9	22.9	22.9
50% Atmospheric NFig (dB)	27.1	27.1	27.1	13.3	13.3	13.3
50% Rural Man-made NFIG (dB)	37.5	37.5	37.5	33.5	33.5	33.5
50% External Noise Fig (dB)	38.2	38.2	38.2	33.9	33.9	33.9
50% System Noise Figure (dB)	38.6	38.6	38.6	34.9	34.9	34.9
50% System Noise Level (dBm)	-121.9	-121.9	-121.9	-125.6	-125.6	-125.6
Co-Chan Interference (dBm)	-111.8	-111.8	-111.8	-107.9	-107.9	-107.9
Adj-Chan Interference (dBm)	-94.3	-106.0	-117.8	-95.1	-105.2	-113.9
Total Interference (dBm)	-94.2	-105.0	-110.8	-94.8	-103.3	-106.9
50% S/N (dB)	48.7	37.0	25.2	-151.5	41.4	32.7
50% S/I (dB)	20.9	20.0	14.0	-182.2	19.1	14.0
50% S/(N+I) (dB)	20.9	19.9	13.7	-182.2	19.1	14.0
99% Ionospheric Loss (dB)	8.3	15.0	28.0	4.8	8.5	16.0
99% Rcvd Signal Level (dBm)	-77.0	-91.7	-109.3	-279.2	-88.0	-100.1
99% Galactic NFig (dB)	29.6	29.6	29.6	26.5	26.5	26.5
99% Atmospheric NFig (dB)	31.9	31.9	31.9	23.1	23.1	23.1
99% Rural Man-made NFIG (dB)	50.0	50.0	50.0	46.0	46.0	46.0
99% External Noise Fig (dB)	50.1	50.1	50.1	46.1	46.1	46.1
99% System Noise Figure (dB)	50.2	50.2	50.2	46.1	46.1	46.1
99% System Noise Level (dBm)	-110.4	-110.4	-110.4	-114.4	-114.4	-114.4
99% S/N (dB)	33.3	18.7	1.0	-164.8	26.3	14.3
99% S/I (dB)	17.2	13.3	1.5	-184.4	15.3	6.9
99% S/(N+I) (dB)	17.1	12.2	-1.8	-184.4	15.0	6.1
Std. Deviation S/(N+I) (dB)	1.7	3.3	6.6	0.9	1.8	3.4
$(S/N)_{req}$ @ 300 bps	5.0	5.0	5.0	5.0	5.0	5.0
$(S/N)_{req}$ @ 600 bps	8.0	8.0	8.0	8.0	8.0	8.0
$(S/N)_{req}$ @ 1200 bps	11.5	11.5	11.5	11.5	11.5	11.5
$(S/N)_{req}$ @ 1800 bps	16.0	16.0	16.0	16.0	16.0	16.0
Margin/Std Dev @ 300 bps	9.6	4.5	1.3	-199.7	8.0	2.7
Margin/Std Dev @ 600 bps	7.8	3.6	0.9	-202.9	6.3	1.8
Margin/Std Dev @1200 bps	5.7	2.5	0.3	-206.7	4.3	0.7
Margin/Std Dev @1800 bps	3.0	1.2	-0.3	-211.5	1.8	-0.6

Table B-6 Nighttime Link Budget, Air-to-Ground Direction

Ground Range D (km)	1000	3000	5000	1000	3000	5000
Carrier frequency (MHz)	5.6	5.6	5.6	8.9	8.9	8.9
Time block	Night	Night	Night	Night	Night	Night
f_oE (MHz)	1.0	1.0	1.0	1.0	1.0	1.0
f_oF2 (MHz)	4.0	4.0	4.0	4.0	4.0	4.0
Reflection height h' (km)	450	450	450	450	450	450
Number of hops	1	1	2	1	1	2
Path length P' (km)	1371	3225	5470	1371	3225	5470
Elev Take-off Angle (deg)	38.7	9.4	13.5	38.7	9.4	13.5
50% MUF (MHz)	6.9	12.2	11.4	6.9	12.2	11.4
Std. Deviation of MUF (MHz)	1.1	1.9	1.8	1.1	1.9	1.8
EIRP (dBm)	48	48	48	48	48	48
Spreading Loss (dB)	110.2	117.6	122.2	114.2	121.7	126.2
50% Over MUF Loss (dB)	0.0	0.0	0.0	203.0	0.0	0.0
50% Ionospheric Loss (dB)	1.4	2.4	4.5	0.7	1.2	2.3
50% Rcvd Signal Level (dBm)	-63.6	-72.0	-78.7	-269.9	-74.9	-80.5
Receive Antenna Loss (dB)	3.0	3.0	3.0	3.0	3.0	3.0
Receiver Noise Figure (dB)	25.0	25.0	25.0	25.0	25.0	25.0
50% Galactic NFig (dB)	34.0	34.0	34.0	29.6	29.6	29.6
50% Atmospheric NFig (dB)	36.2	36.2	36.2	31.2	31.2	31.2
50% Rural Man-made NFIG (dB)	48.1	48.1	48.1	42.3	42.3	42.3
50% External Noise Fig (dB)	48.6	48.6	48.6	42.8	42.8	42.8
50% System Noise Figure (dB)	48.6	48.6	48.6	43.0	43.0	43.0
50% System Noise Level (dBm)	-111.9	-111.9	-111.9	-117.5	-117.5	-117.5
Co-Chan Interference (dBm)	-93.7	-93.7	-93.7	-95.5	-95.5	-95.5
Adj-Chan Interference (dBm)	-84.5	-93.0	-99.7	-87.9	-95.9	-101.5
Total Interference (dBm)	-84.0	-90.3	-92.7	-87.2	-92.7	-94.5
50% S/N (dB)	48.4	39.9	33.3	-152.4	42.7	37.0
50% S/I (dB)	20.5	18.3	14.0	-182.7	17.8	14.0
50% S/(N+I) (dB)	20.5	18.3	14.0	-182.7	17.8	14.0
99% Ionospheric Loss (dB)	1.7	3.1	5.7	0.9	1.5	2.9
99% Rcvd Signal Level (dBm)	-63.9	-72.7	-79.9	-270.1	-75.2	-81.1
99% Galactic NFig (dB)	37.6	37.6	37.6	33.2	33.2	33.2
99% Atmospheric NFig (dB)	54.9	54.9	54.9	42.2	42.2	42.2
99% Rural Man-made NFIG (dB)	60.6	60.6	60.6	54.8	54.8	54.8
99% External Noise Fig (dB)	61.7	61.7	61.7	55.1	55.1	55.1
99% System Noise Figure (dB)	61.7	61.7	61.7	55.1	55.1	55.1
99% System Noise Level (dBm)	-98.8	-98.8	-98.8	-105.4	-105.4	-105.4
99% S/N (dB)	34.9	26.2	19.0	-164.7	30.2	24.3
99% S/I (dB)	20.1	17.6	12.8	-182.9	17.5	13.4
99% S/(N+I) (dB)	20.0	17.1	11.9	-183.0	17.2	13.1
Std. Deviation S/(N+I) (dB)	0.2	0.4	0.5	0.1	0.2	0.4
$(S/N)_{req}$ @ 300 bps	5.0	5.0	5.0	5.0	5.0	5.0
$(S/N)_{req}$ @ 600 bps	8.0	8.0	8.0	8.0	8.0	8.0
$(S/N)_{req}$ @ 1200 bps	11.5	11.5	11.5	11.5	11.5	11.5
$(S/N)_{req}$ @ 1800 bps	16.0	16.0	16.0	16.0	16.0	16.0
Margin/Std Dev @ 300 bps	71.5	25.9	9.9	-1747.3	54.8	22.4
Margin/Std Dev @ 600 bps	57.6	20.0	6.6	-1775.2	41.9	14.9
Margin/Std Dev @1200 bps	41.5	13.2	2.7	-1807.8	26.9	6.2
Margin/Std Dev @1800 bps	20.7	4.4	-2.2	-1849.7	7.7	-5.0

Table B-7 Daytime Link Budget Ground-to-Air Direction

Ground Range D (km)	1000	3000	5000	1000	3000	5000
Carrier frequency (MHz)	13.0	13.0	13.0	17.9	17.9	17.9
Time block	Day	Day	Day	Day	Day	Day
f_oE (MHz)	3.4	3.4	3.4	3.4	3.4	3.4
f_oF2 (MHz)	8.5	8.5	8.5	8.5	8.5	8.5
Reflection height h’ (km)	350	350	350	350	350	350
Number of hops	1	1	2	1	1	2
Path length P’ (km)	1243	3153	5315	1243	3153	5315
Elev Take-off Angle (deg)	32.0	6.0	9.6	32.0	6.0	9.6
50% MUF (MHz)	15.6	27.7	26.0	15.6	27.7	26.0
Std Deviation of MUF (MHz)	2.4	4.3	4.1	2.4	4.3	4.1
EIRP (dBm)	52	52	52	52	52	52
Spreading Loss (dB)	116.7	124.7	129.3	119.4	127.5	132.1
50% Over MUF Loss (dB)	0.0	0.0	0.0	203.0	0.0	0.0
50% Ionospheric Loss (dB)	4.6	8.3	15.5	2.6	4.7	8.8
50% Rcvd Signal Level (dBm)	-69.3	-81.0	-92.8	-273.1	-80.2	-88.9
Receive Antenna Loss (dB)	3.0	3.0	3.0	3.0	3.0	3.0
Receiver Noise Figure (dB)	25.0	25.0	25.0	25.0	25.0	25.0
50% Galactic NFig (dB)	26.0	26.0	26.0	22.9	22.9	22.9
50% Atmospheric NFig (dB)	27.1	27.1	27.1	13.3	13.3	13.3
50% Engine Noise FIG (dB)	37.5	37.5	37.5	33.5	33.5	33.5
50% External Noise Fig (dB)	41.8	41.8	41.8	37.7	37.7	37.7
50% System Noise Figure (dB)	42.0	42.0	42.0	38.1	38.1	38.1
50% System Noise Level (dBm)	-118.5	-118.5	-118.5	-122.4	-122.4	-122.4
Co-Chan Interference (dBm)	-107.8	-107.8	-107.8	-103.9	-103.9	-103.9
Adj-Chan Interference (dBm)	-90.3	-102.0	-113.8	-91.1	-101.2	-109.9
Total Interference (dBm)	-90.2	-101.0	-106.8	-90.8	-99.3	-102.9
50% S/N (dB)	49.3	37.6	25.8	-150.7	42.2	33.5
50% S/I (dB)	20.9	20.0	14.0	-182.2	19.1	14.0
50% S/(N+I) (dB)	20.9	19.9	13.7	-182.2	19.1	14.0
99% Ionospheric Loss (dB)	8.3	15.0	28.0	4.8	8.5	16.0
99% Rcvd Signal Level (dBm)	-73.0	-87.7	-105.3	-130.1	-84.0	-96.1
99% Galactic NFig (dB)	29.6	29.6	29.6	26.5	26.5	26.5
99% Atmospheric NFig (dB)	31.9	31.9	31.9	23.1	23.1	23.1
99% Engine Noise FIG (dB)	54.0	54.0	54.0	50.0	50.0	50.0
99% External Noise Fig (dB)	54.1	54.1	54.1	50.0	50.0	50.0
99% System Noise Figure (dB)	54.1	54.1	54.1	50.1	50.1	50.1
99% System Noise Level (dBm)	-106.4	-106.4	-106.4	-110.4	-110.4	-110.4
99% S/N (dB)	33.3	18.7	1.0	-164.7	26.3	14.3
99% S/I (dB)	17.2	13.3	1.5	-184.4	15.3	6.9
99% S/(N+I) (dB)	17.1	12.2	-1.7	-184.4	15.0	6.2
Std Deviation S/(N+I) (dB)	1.7	3.3	6.6	0.9	1.8	3.4
$(S/N)_{req}$ @ 300 bps	5.0	5.0	5.0	5.0	5.0	5.0
$(S/N)_{req}$ @ 600 bps	8.0	8.0	8.0	8.0	8.0	8.0
$(S/N)_{req}$ @ 1200 bps	11.5	11.5	11.5	11.5	11.5	11.5
$(S/N)_{req}$ @ 1800 bps	16.0	16.0	16.0	16.0	16.0	16.0
Margin/Std Dev @ 300 bps	9.6	4.5	1.3	-199.8	8.0	2.7
Margin/Std Dev @ 600 bps	7.8	3.6	0.9	-203.0	6.3	1.8
Margin/Std Dev @1200 bps	5.7	2.5	0.3	-206.7	4.3	0.7
Margin/Std Dev @1800 bps	3.0	1.2	-0.3	-211.5	1.8	-0.6

Table B-8 Nighttime Link Budget, Ground-to-Air Direction

Ground Range D (km)	1000	3000	5000	1000	3000	5000
Carrier frequency (MHz)	5.6	5.6	5.6	8.9	8.9	8.9
Time block	Night	Night	Night	Night	Night	Night
f_oE (MHz)	1.0	1.0	1.0	1.0	1.0	1.0
f_oF2 (MHz)	4.0	4.0	4.0	4.0	4.0	4.0
Reflection height h' (km)	450	450	450	450	450	450
Number of hops	1	1	2	1	1	2
Path length P' (km)	1371	3225	5470	1371	3225	5470
Elev Take-off Angle (deg)	38.7	9.4	13.5	38.7	9.4	13.5
50% MUF (MHz)	6.9	12.2	11.4	6.9	12.2	11.4
Std Deviation of MUF (MHz)	1.1	1.9	1.8	1.1	1.9	1.8
EIRP (dBm)	52	52	52	52	52	52
Spreading Loss (dB)	110.2	117.6	122.2	114.2	121.7	126.2
50% Over MUF Loss (dB)	0.0	0.0	0.0	203.0	0.0	0.0
50% Ionospheric Loss (dB)	1.4	2.4	4.5	0.7	1.2	2.3
50% Rcvd Signal Level (dBm)	-59.6	-68.0	-74.7	-265.9	-70.9	-76.5
Receive Antenna Loss (dB)	3.0	3.0	3.0	3.0	3.0	3.0
Receiver Noise Figure (dB)	25.0	25.0	25.0	25.0	25.0	25.0
50% Galactic NFig (dB)	34.0	34.0	34.0	29.6	29.6	29.6
50% Atmospheric NFig (dB)	36.2	36.2	36.2	31.2	31.2	31.2
50% Engine Noise FIG (dB)	52.1	52.1	52.1	46.3	46.3	46.3
50% External Noise Fig (dB)	52.3	52.3	52.3	46.5	46.5	46.5
50% System Noise Figure (dB)	52.3	52.3	52.3	46.6	46.6	46.6
50% System Noise Level (dBm)	-108.2	-108.2	-108.2	-113.9	-113.9	-113.9
Co-Chan Interference (dBm)	-89.6	-89.6	-89.6	-91.5	-91.5	-91.5
Adj-Chan Interference (dBm)	-80.5	-89.0	-95.6	-83.9	-91.9	-97.5
Total Interference (dBm)	-80.0	-86.3	-88.7	-83.2	-88.7	-90.5
50% S/N (dB)	48.7	40.2	33.5	-152.0	43.1	37.4
50% S/I (dB)	20.5	18.3	14.0	-182.7	17.8	14.0
50% S/(N+I) (dB)	20.5	18.3	14.0	-182.7	17.8	14.0
99% Ionospheric Loss (dB)	1.7	3.1	5.7	0.9	1.5	2.9
99% Rcvd Signal Level (dBm)	-59.9	-68.7	-75.9	-117.5	-71.2	-77.1
99% Galactic NFig (dB)	37.6	37.6	37.6	33.2	33.2	33.2
99% Atmospheric NFig (dB)	54.9	54.9	54.9	42.2	42.2	42.2
99% Engine Noise FIG (dB)	64.6	64.6	64.6	58.8	58.8	58.8
99% External Noise Fig (dB)	65.1	65.1	65.1	58.9	58.9	58.9
99% System Noise Figure (dB)	65.1	65.1	65.1	58.9	58.9	58.9
99% System Noise Level (dBm)	-95.4	-95.4	-95.4	-101.6	-101.6	-101.6
99% S/N (dB)	35.5	26.8	19.6	-164.5	30.4	24.5
99% S/I (dB)	20.1	17.6	12.8	-182.9	17.5	13.4
99% S/(N+I) (dB)	20.0	17.1	12.0	-183.0	17.3	13.1
Std Deviation S/(N+I) (dB)	0.2	0.5	0.9	0.1	0.2	0.4
$(S/N)_{req}$ @ 300 bps	5.0	5.0	5.0	5.0	5.0	5.0
$(S/N)_{req}$ @ 600 bps	8.0	8.0	8.0	8.0	8.0	8.0
$(S/N)_{req}$ @ 1200 bps	11.5	11.5	11.5	11.5	11.5	11.5
$(S/N)_{req}$ @ 1800 bps	16.0	16.0	16.0	16.0	16.0	16.0
Margin/Std Dev @ 300 bps	74.1	27.5	10.5	-1762.6	55.5	22.6
Margin/Std Dev @ 600 bps	59.8	21.3	7.0	-1790.0	42.5	15.1
Margin/Std Dev @1200 bps	43.0	14.0	2.9	-1823.7	27.3	6.3
Margin/Std Dev @1800 bps	21.5	4.7	-2.4	-1865.9	7.8	-5.0

References

[1] C.C. Watterson, J.R. Juroshek, and W. Bensema, "Experimental Confirmation of an HF Channel Model", IEEE Trans. Communications Technology, V-COM-18, pp 792-803, 1970.

[2] CCIR Report 549-2, "HF Ionospheric Model Simulators", in Reports and Recommendations of the CCIR 1986; Vol III: Fixed Service at Frequencies below about 30 MHz, ITU, Geneva 1986.

[3] J.L. Lloyd, D.L. Lucas, G.W. Haydon, and L.R. Teters, "Estimating the Performance of Telecommunication Systems using the Ionospheric Transmission Channel", NTIA Report 83-127, Institute for Telecommunications Sciences, Boulder, Col., 1983.

[4] A.D. Spaulding and G.H. Hagn, "Worldwide Minimum Environmental Radio Noise Levels (0.1 Hz to 100 GHz)", Effect of the Ionosphere on Space and Terrestrial Systems, Ed. John Goodman, pp 177-182, 1978.

[5] CCIR Report 322, "World Distribution and Characteristics of Atmospheric Radio Noise", Documents of the Xth Plenary Assembly, Geneva, 1963.

[6] K. Davies, Ionospheric Radio Waves, Waltham, MA; Blaisdell, 1969.

[7] D. Lucas and J.D.Harper, "A Numerical Representation of CCIR Report 322 High Frequency (3-30 MC/s) Atmospheric Radio Noise Data", National Bureau of Standards Technical Note 318, August 1965.

[8] J.M. Goodman, J.W. Ballard and E. Sharp, "A Long Term Investigation of the HF Communication Channel over Middle and High Latitude Paths", Radio Science, vol 32, No.4, pp1705-1715, 1997.

[9] M. Abramowitz and I. Stegun, *Handbook of Mathematical Functions,* U.S. Department of Commerce, National Bureau of Standards: Washington, D.C., 1970

[10] CCIR Report 340-1, "Atlas of Ionospheric Characteristics", Oslo, ITU, Geneva, 1966.

[11] K.G.Budden, Radio Waves in the Ionosphere, Cambridge University Press, England, 1966.

[12] CCIR Report 252-2, "CCIR Interim Method for Estimating Skywave Field Strength and Transmission Loss at Frequencies Between the Approximate Limits of 2 and 30 MHz", ITU, Geneva, 1970.

[13] R.A.Wagner, "Modeling the Auroral E-Layer" in Air Force Systems Command Report AFCRL-72-0305, 1972.

[14] Standards and Recommended Practices (SARPs) for HF Data Link, in ICAO Annex 10.

This page intentionally left blank.

Appendix C

METHODOLOGY FOR COMPUTING AVAILABILITY AND CONTINUITY OF SERVICE FOR HF DATA LINK (NORMATIVE)

This page intentionally left blank.

APPENDIX C TABLE OF CONTENTS

APPENDIX C TABLE OF FIGURES

APPENDIX C TABLE OF TABLES

This page intentionally left blank.

Appendix C —Methodology for Computing Availability and Continuity of Service for HF Data Link (Normative)

C.1 Introduction

Availability and Continuity of Service are two of the four key parameters defining the Installed Communications Performance (ICP) of the HF Data Link subnetwork. The purpose of this appendix is to provide a standard methodology for partitioning the system level Availability and Continuity of Service performance to major subsystems. This methodology is more complex than the typical computation of system availability due to two factors:

1. HF Data Link subnetworks are expected to provide service over broad regional or global coverage volumes. Conventional calculation of availability will produce inappropriately low estimates of the system availability, due to the wide-ranging coverage of the HF Data Link systems. That is, under conventional estimates, an outage in any limited region is treated as an outage of the entire coverage volume.

2. The specifications of certain HF Data Link subnetwork performance parameters, such as RF performance and traffic capacity, are given in statistical terms. This introduces the possibility that users may experience service interruptions or outages due to normal statistical fluctuations in the subnetwork performance, even when all components of the subnetwork are operating within their specifications. Such fault-free rare events, which must be considered in the HF Data Link performance, are *not* included in the usual computation of availability.

This appendix is organized in several sections.

Section C.2 summarizes definitions of key parameters used in the computations and provides the important equations used in the methodology. The derivation and rationale for these equations is too extensive for the scope of this appendix. Interested readers are urged to consult [1] for additional details.

Section C.3 defines the measurement methodology for availability.

Section C.4 defines the measurement methodology for continuity.

C.2 Key Analysis Equations

This section defines certain key parameters and equations that are used in establishing the availability and continuity of service performance of the HF Data Link system. Additional detail and examples may be found in RTCA DO-270, which uses a similar methodology.

C.2.1 Availability Analysis Equations

C.2.1.1 Outage Duration

This MASPS defines an outage as an interruption of service having a duration that exceeds 10 times the 95[th] percentile transfer delay. For the purpose of the availability computation, the outage is assumed to have started at the time when service was requested. The outage ends when any data block is delivered to the destination system. This block may be an administrative block transmitted within the subnetwork. The outage duration timing is illustrated in Figure C-1. The outage duration is denoted by the variable T_{OUT}.

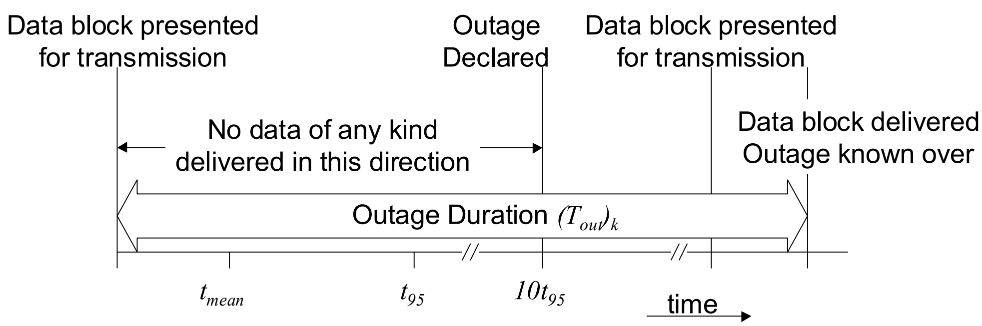


Figure C-1: Timing of Outage Duration Events

The failure to deliver an individual block of information *does not by itself* constitute an outage. It is possible that a single block is not delivered, and yet other blocks, submitted later, are delivered. In this case, there is no outage. This situation is clarified in Figure C-2.

C.2.1.2 Outage Rate/Mean Time Between Outage

Computation of several of the availability factors require an estimate of the average outage rate, λ_{OUT}, or, equivalently, the mean time between outages, $\overline{T_{BO}}$. The average outage rate is the average number of outages occurring in a unit of time. Once the system is operational, it is possible to estimate λ_{OUT} by counting the number of outages N_{OUT}, in an observation time, T_{OBS}. The variables λ_{OUT}, $\overline{T_{BO}}$, N_{OUT} and T_{OBS} are related as shown in Eq. {C-1].

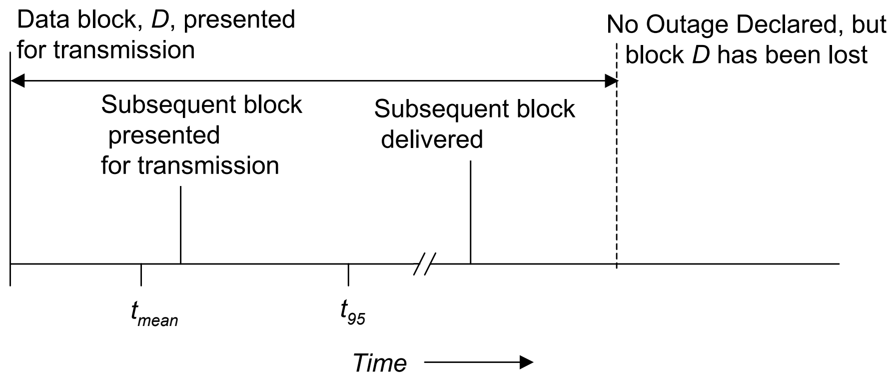


Figure C-2: Example of Non-Delivery that Does Not Result in Outage

$$\lambda_{OUT} = \frac{N_{OUT}}{T_{OBS}} = \frac{1}{\overline{T_{BO}}}$$
$$\overline{T_{BO}} = \frac{T_{OBS}}{N_{OUT}} = \frac{1}{\lambda_{OUT}} \qquad \text{Eq. [C-1]}$$

An implicit assumption in the analysis that follows is that the time between two consecutive outages is an independent random variable that is exponentially distributed with mean $\overline{T_{BO}}$.

C.2.1.3 Outage Restoration Rate/Mean Restoration Time

Computation of several of the availability factors also requires an estimate of the mean restoration time, $\overline{T_R}$. Associated with $\overline{T_R}$ is the outage restoration rate, μ_{OUT}. The "excess outage duration", T_R, is a random variable whose value is independent between outages, the relationship between the number of outages N_{OUT}, the duration of the individual outages, $\{(T_{OUT})_k : k = 1, 2, \ldots N_{OUT}\}$, $\overline{T_R}$ and μ is given by

$$t_R = T_{OUT} - T_{OD}$$
$$\overline{T_R} = E[T_R] = E[T_{OUT} - T_{OD}] = \frac{1}{N_{OUT}} \sum_{k=1}^{N_{OUT}} (T_{OUT})_k - T_{OD}$$
$$= \frac{1}{\mu_{OUT}} \qquad \text{Eq. [C-2]}$$
$$\mu_{OUT} = \frac{1}{\overline{T_R}}$$

Equation Eq. [C-2] introduces a new constant T_{OD}, which is the service outage time threshold declared in the system-specific material. This value is kept as a variable to permit flexibility in matching system performance to the desired operational RCP, subject to the MASPS constraint: $T_{OD} \le 10T_{95}$.

In most of the cases where computations depend on $\overline{T_R}$, it is *only* the average value that is important, and no assumptions about the distribution of the outages times need be made. When it is necessary to assume a distribution, this methodology assumes that the outage restoration times are described by an exponential density function given by

$$p(t_{OUT}) = \begin{cases} \mu_{OUT} e^{-\mu_{OUT} t_{OUT}} & t_{OUT} \geq 0 \\ 0 & elsewhere \end{cases} \qquad \text{Eq. [C-3]}$$

C.2.1.4 Availability Ratio

Traditional practice defines system availability in terms of a computed value called the Availability Ratio. The Availability Ratio is defined over an observation interval, T_{OBS}, as:

$$A_o = \frac{T_{OBS} - \sum_{k=1}^{N_{OUT}} (T_{OUT})_k}{T_{OBS}} = 1 - \frac{N_{OUT} \overline{T_{OUT}}}{T_{OBS}} \qquad \text{Eq. [C-4]}$$

where $\sum (T_{OUT})_k$ is the *total* interval of time within the observation interval when the system is not available for use. In this context, "available for use" means that the system is capable of providing data communications with the specified level of integrity while meeting the 95th percentile transfer delay permitted by the operational application. The approach given in Eq. [C-4], which is widely recognized in the engineering community, describes the availability of a specific system to a specific user at a specific point or over a limited region in space.

C.2.1.5 Geographically Dependent Availability Ratio

This section further develops Eq. [C-4] to account for systems that cover large regions of airspace over a significant portion of the Earth's surface. Such systems may be subject to partial outages that affect users in specific areas at specific times while providing uninterrupted service to users in other coverage volumes. Such transient outages must be carefully factored in to an expression of overall subnetwork availability.

The question of determining the outage durations must now be addressed. It is obvious that a different set of outages $\{T_{kj}\}$ will be observed at each of *j* points in space. If the points are close together, the outages are likely to be the same. Outage durations measured at widely spaced points, however, are likely to be significantly different.

This concept can be expressed mathematically by assigning a three-dimensional vector, $\vec{\mathbf{x}}$, to each element of a set of observation locations, which we call $\Omega = \{\vec{\mathbf{x}}_j : j = 1, 2, 3, ...\}$. Thus, if availability is computed as given in Eq. [C-4], a *different answer* can be expected for each observation location. This means that the availability is a function of both the observation time and the observation locations.

$$A(\vec{\mathbf{x}}_j;T_{OBS}) = 1 - \frac{\sum_{k=1}^{\#\text{ outages in } T_{OBS} \text{ at location } \vec{\mathbf{x}}_j} \left(T_{OUT}(\vec{\mathbf{x}}_j)\right)_k}{T_{OBS}} \qquad \text{Eq. [C-5]}$$

Now let the set of locations, Ω, be the coverage volume declared in the system-specific material.

The average availability over the entire coverage volume is:

$$\overline{A(T_{OBS})} = \int_{\Omega} A(\vec{\mathbf{x}};T_{OBS})\, p_{\vec{\mathbf{x}}}(\vec{\mathbf{x}})\, d\vec{\mathbf{x}} \qquad \text{Eq. [C-6]}$$

where $p_{\vec{\mathbf{x}}}(\vec{\mathbf{x}})$ is the probability density function of users over the coverage volume, Ω.

Eq. [C-6] is an explicit function of the observation location, $\vec{\mathbf{x}}$. Eq. [C-6] can be viewed as the availability seen by an average user of the subnetwork infrastructure. Substituting Eq. [C-5] into Eq. [C-6]:

$$\overline{A(T_{OBS})} = \int_{\Omega} \left[1 - \frac{\sum_k (T_{OUT}(\vec{\mathbf{x}}))_k}{T_{OBS}} \right] p_{\vec{\mathbf{x}}}(\vec{\mathbf{x}})\, d\vec{\mathbf{x}}$$

$$= \int_{\Omega} 1 \times p_{\vec{\mathbf{x}}}(\vec{\mathbf{x}})\, d\vec{\mathbf{x}} - \int_{\Omega} \frac{\sum_k (T_{OUT}(\vec{\mathbf{x}}))_k}{T_{OBS}}\, p_{\vec{\mathbf{x}}}(\vec{\mathbf{x}})\, d\vec{\mathbf{x}} \qquad \text{Eq. [C-7]}$$

$$= 1 - \frac{1}{T_{OBS}} \int_{\Omega} \left[\sum_k (T_{OUT}(\vec{\mathbf{x}}))_k \right] p_{\vec{\mathbf{x}}}(\vec{\mathbf{x}})\, d\vec{\mathbf{x}}$$

In simple language, Eq. [C-7] says that the average availability, $\overline{A(T_{OBS})}$, is affected not only by the total outage duration at each location in coverage, but also by the probability that an aircraft is at that location. This means that outages in high traffic areas, such as the North Atlantic corrider, have a greater impact on overall average system availability than outages in remote areas, such as the South Pacific. Thus, given an approximate distribution of aircraft, Eq. [C-7] provides a framework for both bottom up computation of system availability by accumulating the outage times at many locations *and* top down partitioning into the availability requirements within specific regions. In the partitioning process, the specific regions can be identified as subsets of the coverage volume, Ω.

In real world applications, a continuous probability density function of aircraft as a function of position, $p_{\vec{\mathbf{x}}}(\vec{\mathbf{x}})$ will not be available. Instead, it is expected that the density function will be approximated as a constant over regions of various size. For example, a constant density might be assumed over the North Atlantic track system. When this "area constant" density assumption is made, the continuous integral shown in Eq. [C-7] will become a discrete sum over the different areas. Denote the various regions as ω_m, and the area of those regions as $S(\omega_m)$, and the average probability density over that region as p_{ω_m}, then rewrite Eq. [C-7] as the following discrete sum:

$$1-\frac{1}{T_{OBS}}\int_{\Omega}\left[\sum_k (T_{OUT}(\vec{\mathbf{x}}))_k\right]p_{\vec{\mathbf{x}}}(\vec{\mathbf{x}})d\vec{\mathbf{x}} \approx 1-\frac{1}{T_{OBS}}\sum_m S(\omega_m)p_{\omega_m}\sum_k (T_{OUT}(\omega_m))_k$$
$$=1-\frac{1}{T_{OBS}}\sum_m P_m \sum_k (T_{OUT}(\omega_m))_k \qquad \text{Eq. [C-8]}$$

where P_m is the percentage of all aircraft that are in the region ω_m. Eq. [C-8] will form the basis for the computation of HF Data Link availability.

In Eq. [C-7] and Eq. [C-8], the probability density function is not shown as a function of time. On a time scale ranging from hours to weeks, the probability density functions are certainly a function of time: air traffic in any region ebbs and flows with flight schedules. Similarly, the physics of HF propagation (see Appendix B) vary over time scales of hours to weeks and vary with geographic location. Therefore, the number and duration of outages will also vary with time and geographic location. But Eq. [C-7], and Eq. [C-8], anticipate an availability observation time of at least several months, and the MASPS defines an observation time of 365 days. Furthermore, when computing regional performance, Eq. [C-8], effectively averages over the entire region, Ω. Over these observation times and extended regions, the any changes in aircraft density average out, leaving a constant average aircraft density for each region or position. Therefore, the time-dependence of the density functions is not considered in this formulation.

Note: Inclusion of time dependence can be added, if necessary, by making the probability density functions depend on two variables – position and time – and integrating over the observation time.

C.2.1.6 Availability Calculation Using Independent Elements

When the subsystem consists of independent serial elements, the overall availability of a complex system is equal to the product of the availability ratios for the individual elements; that is:

$$A_{oSYS} = A_{o1}\times A_{o2}\times A_{o3}\times\cdots\times A_{oN} \qquad \text{Eq. [C-9]}$$

where N is the number of elements.

The various terms in Eq. [C-9] could, in turn, be computed by applying Eq. [C-7] to each domain or source of unavailability. This suggests that perhaps Eq. [C-7] could be applied directly, and the contributions of the various domains could be partitioned by means of a simple summation, rather than the product shown in Eq. [C-9]. It is a simple matter to show that such a summation-based partitioning using Eq. [C-7] forms a *lower bound* for the multiplicative partitioning of Eq. [C-9], and that this bound is quite tight when the unavailability in each domain is significantly less that $\frac{1}{N}$. That is, the summation methodology and the product methodology give the same answer under the condition:

$$1-\sum_{k}^{N}\varepsilon_k \le \prod_k (1-\varepsilon_k) \text{ whenever } 0 \le \varepsilon_k << \frac{1}{N} << 1$$
$$\varepsilon_k = \frac{(T_{OUT})_k}{T_{OBS}} \qquad \text{Eq. [C-10]}$$

In some cases, it is easier to compute the probability that a service outage occurs directly, rather than by summing the outages. In these cases, Eq. [C-9] is a more appropriate method for computing the availability effects. In other cases, it is simpler to estimate or measure the outage durations, and Eq. [C-7] is more appropriate. From the viewpoint of this methodology, either method is acceptable. Outages that have significant spatial as well as temporal variation should use Eq. [C-7].

The measurement methodology described in C.3 accounts for all of the various availability factors except the loading factor, which cannot be controlled during operational measurements. Therefore, determination of HF Data Link availability performance will adjust the measured availability by a computed factor to account for the higher traffic loading specified in the Traffic Model of Appendix E, or other more stringent traffic model declared by the service provider.

C.2.1.7 Availability Effects of Traffic Loading

The availability of a communications system with limited resources is typically computed by means of either the Erlang-B or Erlang-C formulas. The Erlang-B formula assumes that a request for service must either be served immediately or dropped immediately. There is no queueing for service in the Erlang-B model. The Erlang-C model assumes that a request for service is either served immediately or placed at the end of a (possibly infinite) queue for service on a "first-in-first-out" basis. Depending on the specific HF Data Link ground station architecture, either, both, or some intermediate form of these formulas might be appropriate.

Regardless of HF Data Link ground station architecture, however, use of the Erlang-B formula provides a pessimistic estimate of availability. Therefore, it is permissible to use an Erlang-B analysis to estimate the availability effects due to traffic loading. The Erlang-B formula, *B(c,a)*, is given by:

$$B(c,a) = \frac{\frac{a^c}{c!}}{\sum_{n=0}^{c} \frac{a^n}{n!}} \qquad \text{Eq. [C-11]}$$

where the parameters are given in Table C-1.

For architectures that provide queueing or buffering of the HF Data Link messages, the Erlang-B result may be unacceptably pessimistic. A more accurate, but more computationally intense, model requires identification of all of the parameters shown in Table C-1.

The parameters used in the computations shall be consistent with the values declared in Table 2-1 of the MASPS, the values declared in Appendix B, and with the overall HF

Data Link traffic declared in the Traffic Model required by MASPS Section 2.2.5.1.1. For the purposes of this computation, distinctions between HF Data Link priority levels are ignored, and it is assumed that HF Data Link demand of any priority experiences at most an insignificant delay due to the implementation of the priority, precedence, and preemption mechanisms required by the MASPS.

Table C-1: Declared and Derived Parameters for Traffic Load Analysis

λ	average HF Data Link service demand rate	messages/frame
N_{BLOCK}	average HF Data Link message length defined at Pt B or Pt C	time slots/message
R_D	nominal user service rate per server through the HF Data Link system viewed at Pt. B or Pt. C	time slots/frame
c	number of servers available in a single frame	unitless
N_Q	size of queue or buffering supporting AM(R)S service	unitless
T_{OD}	outage definition time	seconds
$\mu = R_D / N_{BLOCKS}$	average block service rate	messages / frame
$a = \lambda/\mu = \lambda N_{BLOCK} / R_D$	average traffic intensity	Erlangs
$\rho = a / c = \lambda/(c\mu)$ $= (\lambda N_{BLOCK})/(cR_D)$	average traffic intensity per server	Erlangs per server
$K = c + N_Q$	maximum system user population	blocks

Using the values declared in Table C-1, the unavailability due to random traffic overloading is computed using Eq. [C-12], Eq. [C-13], and Eq. [C-14].

$$B_K[c,a] = \Pr\{\text{new data block is denied service}\}$$

$$= \frac{\dfrac{a^K}{c!c^{K-c}}}{\left[\displaystyle\sum_{k=0}^{c-1} \frac{a^n}{n!} + \frac{a^c}{c!}\right]} \qquad \text{Eq. [C-12]}$$

$$C_K[c,a] = \Pr\{\text{new block is placed in queue}\}$$

$$= \frac{\dfrac{a^c}{c!}}{\left[\left(\dfrac{1-\rho}{1-\rho^{K-c+1}}\right)\displaystyle\sum_{k=0}^{c-1}\frac{a^n}{n!}+\frac{a^c}{c!}\right]} \qquad \text{Eq. [C-13]}$$

$$U_{LOAD}(T_{OD}) = \Pr\{\text{system service time is greater than } T_{OD}\}$$

$$= \frac{C_K[c,a]}{1-\rho^{K-c+1}}\left[\rho^{K-c}(1-\rho)+e^{-c\mu T_{OD}}\sum_{m=0}^{K-c-1}(1-\rho^{K-c-m})\frac{(a\mu T_{OD})^m}{m!}\right]+B_K[c,a] \qquad \text{Eq. [C-14]}$$

$$A_{LOAD} = 1 - U_{LOAD}$$

Note: Users are cautioned that $B_K(c,a)$ and $C_K(c,a)$ should not be confused with the standard B(c,a) (Erlang-B) and C(c,a) (Erlang-C) notation, and must be computed by Eq. [C-12] and Eq. [C-13], respectively.

Users desiring additional detail are referred to [1].

C.2.1.8 Effect of Redundancy on Availability Calculations

An effective design option for increasing both availability and continuity of service is the inclusion of redundant elements. The effect of redundant elements on availability depends on the service outage rate, the number of redundant paths provided, the observation time, the mission time, and the service restoration rate. The restoration rate is particularly important in the availability computation, but plays little or no role in the continuity of service analysis.

C.2.1.8.1 *K*-redundancy with common repair

In this model, there are K identical elements, of which only one is needed to maintain AM(R)S service. Failed units are repaired through a common repair facility with a fixed limited capacity. The average failure rate is λ_{OUT}, as defined in Section C.2.1.2, and the average restoration rate is μ_{OUT}, as defined in Section C.2.1.3. The model assumes that the service times and restoration times are exponentially distributed. The availability of service through the *K* elements with common repair is given by Eq. [C-15].

$$p_K = \Pr\{\text{ All } K \text{ units are simultaneously under repair}\}$$

$$= K!\left(\frac{\lambda_{OUT}}{\mu_{OUT}}\right)^K \times B(K,\frac{\lambda_{OUT}}{\mu_{OUT}}) \qquad \text{Eq. [C-15]}$$

$$A_{KC} = 1 - p_K$$

This model is appropriate for use with multiple AS installations on the same aircraft. In general, this is not the appropriate model for failures of redundant GS stations serving the same coverage volume unless the same maintenance resources serve both of the affected stations.

C.2.1.8.2 *K*-redundancy with independent repair

In this model there are again K identical elements, but the repair processes are independent of each other. In this case, the availability is

$$A_{KI} = 1-(1-A_o)^K = 1-\left(\frac{\lambda_{OUT}}{\mu_{OUT}}\right)^K \qquad \text{Eq. [C-16]}$$

This model may be appropriate for stations that provide redundant service, but are served by independent maintenance crews. It is not appropriate for installations with multiple AS stations.

C.2.1.8.3 *K*-redundancy without repair

In this model, there are K identical independent units which are allowed to fail without replacement.

$$A_{KN} = 1-\left(1-e^{-\lambda_{OUT}T_{OBS}}\right)^K \approx 1-(\lambda_{OUT}T_{OBS})^K \text{ for } \lambda_{OUT}T_{OBS} << 1. \qquad \text{Eq. [C-17]}$$

C.2.2 Continuity of Service Analysis Equations

Continuity of service is frequently thought about as merely a "short term availability". While simple enough for a very high-level discussion, this view is flawed and does not always give the correct interpretation to more detailed questions.

Availability is an instantaneous probability that HF Data Link services is usable in a given location at any time. There is no "time" associated with the experiment of sampling the availability: the service can be used or it cannot. An *estimate* of the true availability by is obtained from the *availability ratio*. Eq. [C-4] indicates that the availability ratio is computed by recording the total duration of all outages over some observation interval. Nevertheless, the appearance of time into the availability equations is generally for the purpose of estimation only.

On the other hand, continuity of service is directly associated with a specific time interval, known as the continuity of service interval, T_{COS}, which is declared in Table 2-1 of the MASPS. Continuity of service is defined as the conditional probability that a service will continue to be available *over that period of time*, given that it was available at the start of that time. A continuity of service event is *any* disruption or disruptions of service over the specific continuity of service interval, such that the interruption lasts for at least a time interval of T_{SI}. Continuity of service may also be estimated by measuring the number and duration of outages over some observation interval and extrapolating the curve backwards to interruptions of duration T_{SI}.

Continuity, therefore, is *not* just the short-term availability, but depends on the number and frequency of service interruptions.

For example, consider an communications system that offers service over the North Atlantic air routes. Assume that over a particular year of operation, there were 12 outages due to all causes measured in this region, for a total of 8.76 hours. Then by application of Eq. [C-4], the availability ratio for the system is:

$$\begin{aligned} A_o &= 1 - \frac{8.76 \text{ hours}}{8760 \text{ hours}} \\ &= 1 - 1 \times 10^{-3} \\ &= 0.999000 \end{aligned} \qquad \text{Eq. [C-18]}$$

Now consider a second communication system offering the same service, and assume that it experienced 240 outages of average 2 minutes each, for a total of 480 minutes. Again applying Eq. [C-4]:

$$\begin{aligned} A_o &= 1 - \frac{8 \text{ hours}}{8760 \text{ hours}} \\ &= 1 - 9.13 \times 10^{-4} \\ &= 0.999087 \end{aligned} \qquad \text{Eq. [C-19]}$$

So the second system, having less total outage time, has slightly better availability.

But the average rate of outages is much higher for the second system.

$$\begin{aligned} \lambda_{OUT1} &= \frac{12 \text{ outages}}{8760 \text{ hours}} = 0.0014/\text{hour} \\ \lambda_{OUT2} &= \frac{240 \text{ outages}}{8760 \text{ hours}} = 0.0274/\text{hour} \end{aligned} \qquad \text{Eq. [C-20]}$$

Ignoring, for the moment, the distinction that the between service outage time, T_{OD} and service interruption time T_{SI}, the entire air-to-ground subnetwork can be viewed as a single server and Eq. [C-17] applied with $K = 1$ and $T_{COS} = 15 \text{ min} = 0.25 \text{ hour}$:

$$\begin{aligned} COS &\approx 1 - \left(1 - e^{-\lambda_{OUT} T_{COS}}\right)^1 \\ &\approx 1 - (\lambda_{OUT} T_{COS}) \\ COS_1 &\approx 1 - 0.0014 T_{COS} = 0.99965 \text{ for } T_{COS} = 0.25 \text{ hour} \\ COS_2 &\approx 1 - 0.0274 T_{COS} = 0.99315 \text{ for } T_{COS} = 0.25 \text{ hour} \end{aligned} \qquad \text{Eq. [C-21]}$$

So the second system, with more frequent, but shorter, outages has slightly *better* availability but significantly *worse* continuity of service.

Computing the continuity of service requires an estimate of the appropriate rate, λ_{COS}, of Continuity of Service events, where the events are defined defined in Section 2.2.5.4.1 of MASPS. In a manner analogous to the *Availability Ratio* defined in Section C.2.1.4. This rate can be estimated by counting these events over an observation interval:

C.2.2.1 Rate of Continuity of Service Events

In a direct analogy to Section C.2.1.2, the average rate of Continuity of Service events can be estimated by observing the number of events, N_{COS}, over an observation time, T_{OBS}. The rate is estimated in the same manner as in Eq. [C-1]:

$$\lambda_{COS} = \frac{N_{COS}}{T_{OBS}} \qquad \text{Eq. [C-22]}$$

C.2.2.2 Geographically Dependent Continuity of Service Event Rate

Just as the number and duration of outages varies with aircraft location as discussed in Section C.2.1.5, the number of continuity of service events may also vary. Thus, the geographically averaged rate of Continuity of Service events, $\overline{\lambda_{COS}}$, is given by

$$\overline{\lambda_{COS}} = \frac{1}{T_{OBS}} \int_{\Omega} N_{COS}(\vec{\mathbf{x}}) p_{\mathbf{x}}(\vec{\mathbf{x}}) d\vec{\mathbf{x}}, \qquad \text{Eq. [C-23]}$$

where $N_{COS}(\vec{\mathbf{x}})$ is the number of continuity of service events occurring at the location $\vec{\mathbf{x}}$, and the other terms are as defined in the discussions accompanying Eq. [C-7]. Simplification of Eq. [C-23] by a finite sum of area-wise constant probability functions, as described in Eq. [C-8] is appropriate. The corresponding simplification is:

$$\begin{aligned} \overline{\lambda_{COS}} &= \frac{1}{T_{OBS}} \sum_{k} \left(N_{COS}\right)_k \int_{\omega_\kappa} p_{\mathbf{x}}(\vec{\mathbf{x}}) d\vec{\mathbf{x}} \\ &= \frac{1}{T_{OBS}} \sum_{k} \left(N_{COS}\right)_k p(\omega_k) \end{aligned} \qquad \text{Eq. [C-24]}$$

As was the case in availability, the continuity of service can be estimated by a product methodology analogous to Eq. [C-9].

$$COS = C_1 \times C_2 \times \cdots \times C_N \qquad \text{Eq. [C-25]}$$

where N is the number of sources of Continuity of Service Events, and C_n is the Continuity of Service effect due to the *n*-th source.

As in the case of availability described earlier, the measurement methodology discussed in C.3 will require an adjustment to the estimate of the Continuity of Service to account for the traffic loading of the Traffic Model described in the MASPS.

C.3 HF Data Link Availability Measurement

This section presents an acceptable method for calculating availability from spatial and temporal information inherent in HF Data Link messaging. Methods for both global and regional calculations are provided. These methods account for all sources of non-availability of service including: the HF avionics being in voice mode, low SNR, and malfunctioning aircraft or ground elements regardless of whether the root cause of the malfunction is hardware or software.

The unit of analysis is an aircraft flight leg. The approach is to empirically construct the service up/down timeline for each flight leg. If an interruption of service having a duration that exceeds T_{OD} is detected, an outage is declared and the *entire* outage time (not just the time greater than T_{OD}) is counted against availability.

The method described here is to apply a modified version of Eq. [C-8] by utilizing measured data from operational flights. If the communications are confirmed at some regular interval, Δt, then a single flight of duration T_{FLIGHT} can be viewed as providing $M = \frac{T_{FLIGHT}}{\Delta t}$ position samples along the flight path. For regional coverage, T_{FLIGHT} must be interpreted as the flight time within the regional coverage volume. Each such flight will experience some number, k, outages. Because the measurements are taken at the points where the aircraft actually flew, $P_m = 1$. Applying these terms to Eq. [C-8]:

$$\begin{aligned} A &= 1 - \frac{1}{T_{OBS}} \sum_m P_m \sum_k (T_{OUT}(\omega_m))_k \\ &= 1 - \frac{1}{T_{OBS}} \sum_m \left(T_{OUT}\right)_m \\ &= \frac{T_{FLIGHT} - \sum_m \left(T_{OUT}\right)_m}{T_{FLIGHT}} \end{aligned} \qquad \text{Eq. [C-26]}$$

where the sum on k drops out because only a single sample is taken at each position. For a single flight, the observation time, T_{OBS}, is simply the flight time, T_{FLIGHT}. To get multiple samples at each position, and to increase the number of positions, the availability estimates from many flights are averaged together.

$$\begin{aligned} \overline{A} &= \frac{1}{N} \sum_{n=1}^{N} A_n \\ &= 1 - \frac{1}{N} \sum_{n=1}^{N} \frac{1}{\left(T_{FLIGHT}\right)_n} \sum_{m=1}^{M_n} \left(T_{OUT}\right)_m \end{aligned} \qquad \text{Eq. [C-27]}$$

where there are N flights, each with duration $\left(T_{FLIGHT}\right)_n$, and M_n is the number of sample points on the n-th flight.

For the computation of global availability, the entire flight leg is audited for all valid flights. That is, the value of M_n is computed using the entire flight duration. Section C.3.2 details the process to be used to determine $\left(T_{OUT}\right)_m$ and T_{FLIGHT} for global availability.

For regional availability, only flight legs that substantially traverse the region of interest are considered. Of these flights, only the portion of the flight within the region is used for computation of M_n. Section C.3.3 details the process to be used to determine $(T_{OUT})_m$ and T_{FLIGHT} for regional availability.

For both global and regional availability, when the value of $\overline{A}$ has been determined based on measured data, it shall be adjusted to account for the Traffic Model by the process detailed in Section C.3.3.4.

C.3.1 Rules for Determination of Outages from Measured Data

The outage and flight duration information is derived from messages sent from the AS to the GS. Some messages provide latitude, longitude and a timestamp for the latitude and longitude.[1] The time of reception on the ground of each block is recorded, and all of these values are recorded for calculation of T_{FLIGHT}.

Note: Because downlink availability is highly correlated with uplink availability, only downlinks are used in this methodology for computing system availability.

The times at which HF Data Link communications transitions from down to up and from up to down are inferred from the downlink message information as follows:

- Transition from one ground station to another as indicated by a Log On message sent by the aircraft to establish a connection with the new station.

- Log On messages to re-establish the connection with a ground station after the aircraft has lost connection. Loss of connection may be caused by any of the following:

    - Too many NAKS

    - Squitters no longer received

    - HF data disabled; i.e., aircraft in HF voice operation

    - Ground station frequency change noticed received

    - Station/Channel down notice

    - Poor uplink channel quality

- An extended gap in communication. A loss of communication is declared if messages are not received for some length of time.

For the purposes of availability and continuity of service computations, invalid data may be removed from the data set before calculations are made. Examples of invalid data include:

- Data from aircraft that are not customers of the service provider

[1] The records themselves are not time-critical, and can be received at the ground any time from a few seconds to many minutes after their generation within the aircraft. The key information is the time and position information contained *within* the records.

- Data from any flight with a sequence of position events that indicate the aircraft executed an unrealistic flight maneuver

- Data from flights with sequences of position events that indicate an aircraft is reporting exactly the same latitude or longitude for significant duration

- Data from aircraft with failed avionics

- Data from time intervals during which HF Data Link avionics have been intentionally disabled

- Data from non-compliant avionics.

If other invalid data is excluded from the availability computation, the exclusion shall be justified in the system-specific material.

The recorded times are used to construct the service up/down timeline on a per flight leg basis as shown in Figure C-3(a). Both global and regional availability shall be calculated from the timelines in accordance with the rules of Section C.3.2 and C.3.3. The full flight leg timeline is used for global availability calculations. For regional availability, the segment of the time line for which the aircraft is in the region is used. The position information is used to determine the times the aircraft entered and left the region. The regional evaluation time interval starts with the entry event and stops with the exit event.

The availability is calculated as follows. Identify all service interruption episodes of duration less than T_{OD} as shown in Figure C-3(b). These episodes are eliminated from the data to create the outage time line, as shown in Figure C-3(c). The availability, whether global or regional, is the proportion of time that the outage time line (Figure C.3(c)) is up, calculated over all applicable timeline segments.

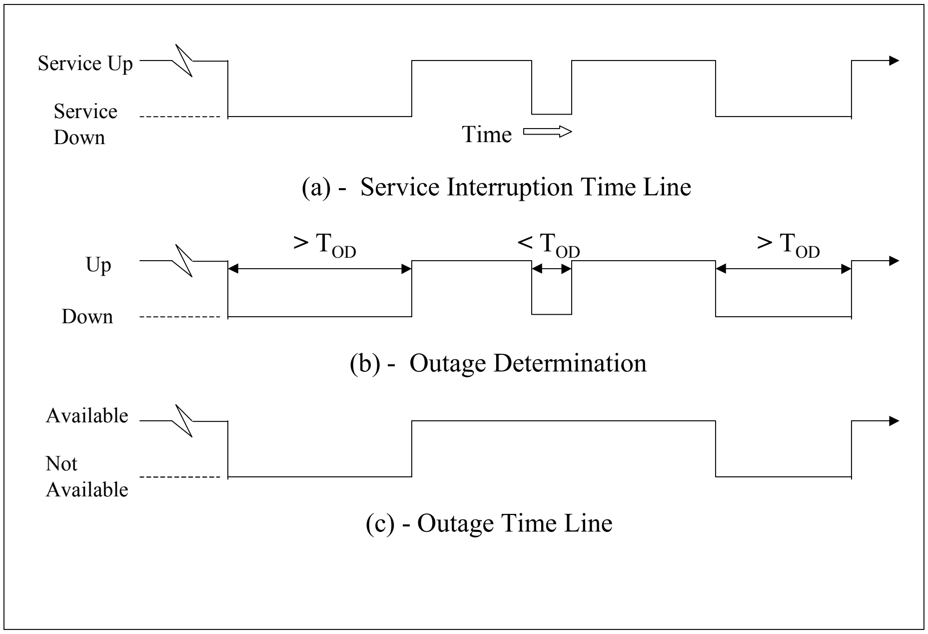


Figure C-3: Example of Service Outage Determination

C.3.2 Global Availability Calculations

Global availability is calculated by applying the rules for outage determination (Section C.3.1) and availability calculation (Eq. [C-26] to valid flight leg timelines for the observation interval.

C.3.3 Regional Availability Calculation

Regional availability is calculated by applying the rules for outage determination (Section C.3.1) and availability calculation (Eq. [C-26]) using data from segments of flight leg timelines that fall within a specific coverage region.

The aircraft latitude, longitude and time information is used to determine the segment time interval via calculations of regional entry and exit times. Only communications within the region will be considered for the computation of regional availability. Data from a segment of length less than that specified in Section C.3.3.2 is not included in the availability calculation.

C.3.3.1 Regions Defined as Spherical Polygons

Calculations of region entry and exit transit times using great-circle-based extrapolations and interpolations of position and time are more accurate than linear methods. For this reason, it is preferable to represent declared coverage as a spherical polygon defined by a set of points on the surface of the Earth with the points connected by great circle arcs. Beginning with the first instance of service during the flight under analysis, assume that the aircraft travels a great-circle arc between this initial point and the position corresponding to the last successful communication before a service outage. Repeat this process as necessary for all of pairs of "service start" and "last successful communication" points. Each great-circle arc is called a "service arc". The endpoints of each arc are defined by a time, a latitude, and a longitude.

Perform a similar computation to extrapolate aircraft position through service outages by establishing a great-circle arc between the "last successful communication" points and the succeeding "service start point". Each such arc is called a "connecting arc". The endpoints of each arc are defined by a time, a latitude, and a longitude.

C.3.3.2 Is Flight Track Within Region Long Enough

The length of a regional flight track segment is determined by summing the distance of each service arc and the connecting arcs. If a service arc straddles a regional boundary, then the distance of the arc within the region can be determined by great circle interpolation. If there is a gap between the first or last arc and the boundary, then the distance of the arc is added to the distance from the boundary to the arc end closest to the boundary.

If the length of the regional flight track segment is sufficiently long, then the flight shall be included in the availability computation.

Note: "Sufficiently long" will be negotiated with regional CAA authorities based on the structure of the regional polygon.

C.3.3.3 Regional Evaluation Time Interval

Both entry and exit transit times are calculated by interpolation or extrapolation of service arcs. The arcs and their extrapolations are segments of great circles.

C.3.3.4 Adjustment for Traffic Loading

The data used to compute availability using Eq. [C-27] will be collected with traffic loading of opportunity. This is generally expected to be less than the loading established by the Traffic Model of Appendix E. The following procedure shall be used to adjust the availability determined by measured data for the Appendix E traffic.

1. Using the Traffic Model of Appendix E, or other model with increased loading, estimate the total number of messages (uplink + downlink) and use that number to establish the values required by Table C-1.

2. Using the values thus established, estimate the Traffic Loading availability factor, A_{LOAD}, using

$$A_{LOAD} \geq 1 - B[c,a] \qquad \text{Eq. [C-28]}$$

where $B[c,a]$ is given by Eq. [C-11], and the arguments are given in Table C-1.

3. Multiply the availability estimate from Eq. [C-27] by the value of A_{LOAD}. If the result meets the desired availability level, the process is complete.

4. If the results of Step 3 do not meet the desired availability level, use the values established in Table C-1 to calculate a more accurate estimate of A_{LOAD} by means of Eq. [C-14].

Note: Because the Erlang B formula given by Eq. [C-11] is an upper limit *on the probability of an outage, the value of A_{LOAD} calculated in Step 2 establishes a* lower limit *on the availability effects of traffic loading. That is, the result of Step 3 is an unduly pessimistic estimate of real-world performance. The adjustment of Step 4 and Step 5 creates a more realistic estimate, at the cost of a more complicated computation.*

5. Multiply the availability estimate from Eq. [C-27] by the value of A_{LOAD}. If the result does not meet the desired availability level, changes to system parameters affecting the contents Table C-1 may be required.

An example of this process is given in C.3.3.5.

C.3.3.5 Example Adjustments for Traffic Loading

This section presents an example of how the adjustment for traffic loading is to be done. Assume that the computation of Eq. [C-27] has been performed for the coverage area of interest, and results in an availability estimate $\overline{A} = 0.925$.

Consider the loading under an ATN operating environment as specified by Appendix E. Under these conditions, most messages can be transmitted within a single time slot within the 32 second HF Data Link Frame. In fact, there will be frequent opportunities to combine messages within the same time slot. Assume that a flight along the longest path through the coverage volume takes 8 hours, and that there are consistently 50 aircraft logged on to a single communications channel during this time. Under these conditions, Appendix E model gives a message rate (up + down) of 5.8 messages per 32 second frame. Then Table C-1 is filled out as shown in Table C-2.

Using the values of c and $a = \dfrac{\lambda}{\mu}$, compute the Erlang B blocking probability, in accordance with Eq. [C-11].

$$B[c,a] = B[12,5.8] = 0.0092 \qquad \text{Eq. [C-29]}$$

Applying this value to Eq. [C-28], $A_{LOAD} = 1 - 0.0092 = 0.9908$.

The adjusted availability estimate, A is then

$$\begin{aligned} A &= \overline{A} \times A_{LOAD} \\ A &= 0.925 \times 0.9902 = 0.916 \end{aligned} \qquad \text{Eq. [C-30]}$$

It is this value that is compared with the system requirement.

Table C-2: Parameters for ATN Loading Example

λ	5.8	messages/frame
N_{BLOCK}	1.0	time slots/message
R_D	1.0	time slots/frame/server
c	12	dimensionless
N_Q	n/a for example	dimensionless
T_{OD}	960	seconds
$\mu = R_D / N_{BLOCKS}$	1	messages / frame/server
$a = \lambda/\mu = \lambda N_{BLOCK} / R_D$	5.8	Erlangs (/server)
$\rho = a / c = \lambda/(c\mu)$ $= (\lambda N_{BLOCK})/(cR_D)$	0.483	Erlangs (per HF Data Link channel)
$K = c + N_Q$	n/a for example	messages

C.4 HF DATA LINK CONTINUITY MEASUREMENT

As discussed in Section C.2.2, continuity of service is directly associated with a specific time interval, known as the continuity of service interval, T_{COS}, which is declared in Table 2-1 of the MASPS. Continuity of service is defined as the conditional probability that a service will continue to be available *over that time interval*, given that it was available at the start of the interval. A continuity of service event is *any* disruption or disruptions of service over the specific continuity of service interval, such that the interruption lasts for at least a time interval of T_{SI}.

By analogy to Eq. [C-27], the average outage rate, $\overline{\lambda_{COS}}$, may be estimated from recorded flight data as

$$\overline{\lambda_{COS}} = \frac{1}{N}\sum_{n=1}^{N}\left(\frac{1}{T_{FLIGHT}}\right)_n \left(N_{OUT}\right)_n \qquad \text{Eq [C-31]}$$

where there are N flights, each with duration $\left(T_{FLIGHT}\right)_n$, and $\left(N_{OUT}\right)_n$ is the number of continuity of service outages experienced on the n-th flight.

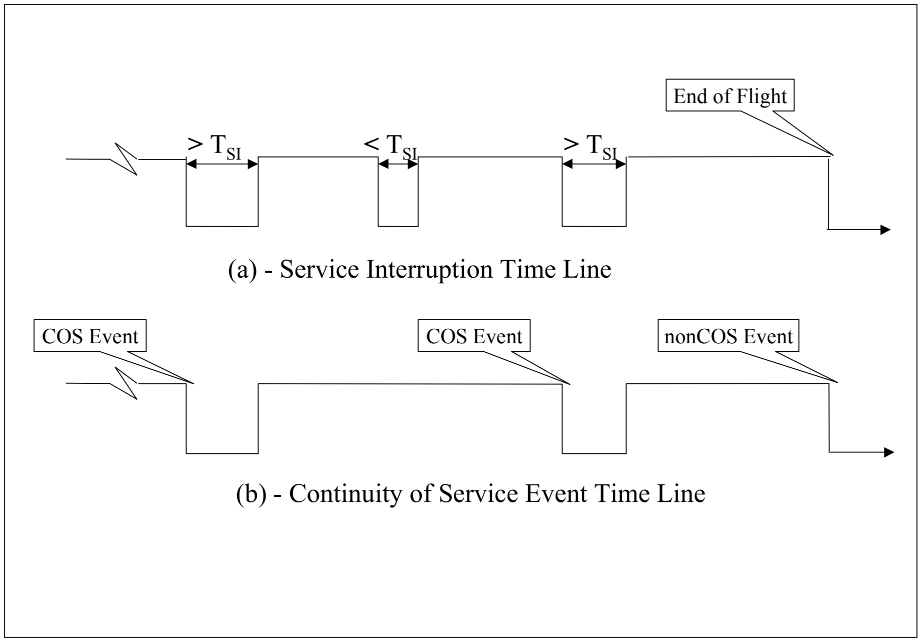


Figure C-4: Continuity of Service Analysis Procedures

Continuity shall be estimated from the same flight-timeline data set that was used to support availability calculations. The estimation procedure illustrated in Figure C-4 is performed on each flight time line or flight time line segment within a region as follows

1. As shown in Figure C-4, use the Service Interruption timeline to construct a Continuity of Service event timeline that shows the service being up for all interruptions of service with duration less than T_{SI} .

2. Designate each up-to-down transition in the Continuity of Service Event Time Lines as a COS event, except those that occur at the end of a flight.

3. Count all of the COS events and sum up the evaluation times for all of the applicable flights.

4. Calculate the average outage rate using Eq. [C-31].

5. Calculate the continuity according to Eq. [C-21].

References

[1] A. O. Allen, *Probability, Statistics and Queueing Theory with Computer Science Applications,* Boston: Academic Press, 1990

This page intentionally left blank.

Appendix D

ANALYSIS OF HF DATA LINK INTEGRITY

This page intentionally left blank.

APPENDIX D TABLE OF CONTENTS

TABLE OF FIGURES

This page intentionally left blank.

Appendix D– Analysis of HF Data Link Integrity

D.1 INTRODUCTION

This appendix addresses the Integrity requirement stated in Section 2.2.5.2 of the MASPS. This requirement is equivalent to the Residual Packet Error Rate requirement of paragraph 3.3.5.1 of the HF Data Link SARPs. This analysis assumes that the HF Data Link system complies with the ICAO Document 9741.

D.2 ANALYSIS

The Integrity requirement of Section 2.2.5.2 in the MASPS mandates that a HF Data Link user packet of 128 octets be delivered with a probability of undetected errors of less than 10^{-6}.

D.2.1 HF Data Link Message Segmentation

When transmitting a user packet, the HF Data Link Aircraft Station or Ground Station Subsystems append various levels of headers to the user packet as well as frame check sequences for error detection. The process of packet construction is shown in Figure D-1. The HF Data Link Subnetwork Layer appends a three octet header to the user packet to create a 131 octet HF Network Protocol Data Unit (HFNPDU). The Link layer then segments the 131 octet HFNPDU into three Basic Data Units (BDUs) of 53 octets or less, appends a two octet header and a two octet (16 bit) FCS to each BDU to create three Link layer Protocol Data Units (LPDUs) of 57 octets or less each. Depending on the implementation, the segmentation of the 131 octet HFNPDU may result two 57 octet LPDUs and one 29 octet LPDU, or in three equal size (or as nearly equal size as possible) LPDUs with 47 or 48 octets each, as shown in Figure D-1. For the purpose of developing the analysis to follow, it will be assumed that a 128 octet user packet results in the transmission of one 47 octet and two 48 octet LPDUs, each of which includes a 16 bit frame check sequence (FCS) for error detection. Each of the LPDUs may then be transmitted in a single TDMA slot or in separate slots depending on the data rate at which the HF Data Link Aircraft Station and Ground Station Subsystems are using to exchange data.

If the HF Data Link channel is operating at a data rate of 300 bits per second (bps), each time slot can accommodate an MPDU consisting of a header with only a single associated LPDU. In this case, the MPDU header is reduced from 11 octets to 9 octets, and three consecutive MPDUs are required to send the message. The resultant structure for a 300 bps channel is shown in Figure D-2. This partitioning has slightly *better* integrity than that shown in Figure D-1.

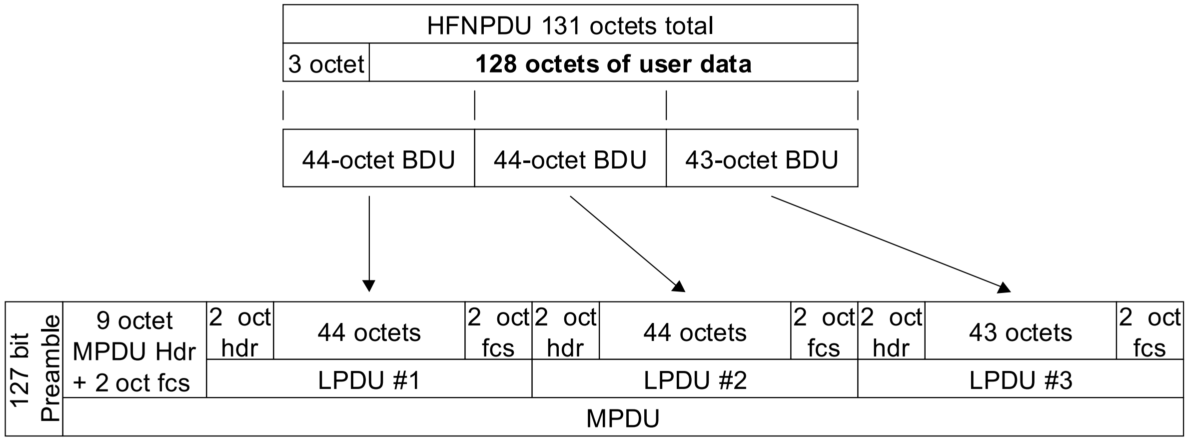


Figure D-1: **Structure of 128-octet Message on HF Data Link Reliable Link Service**

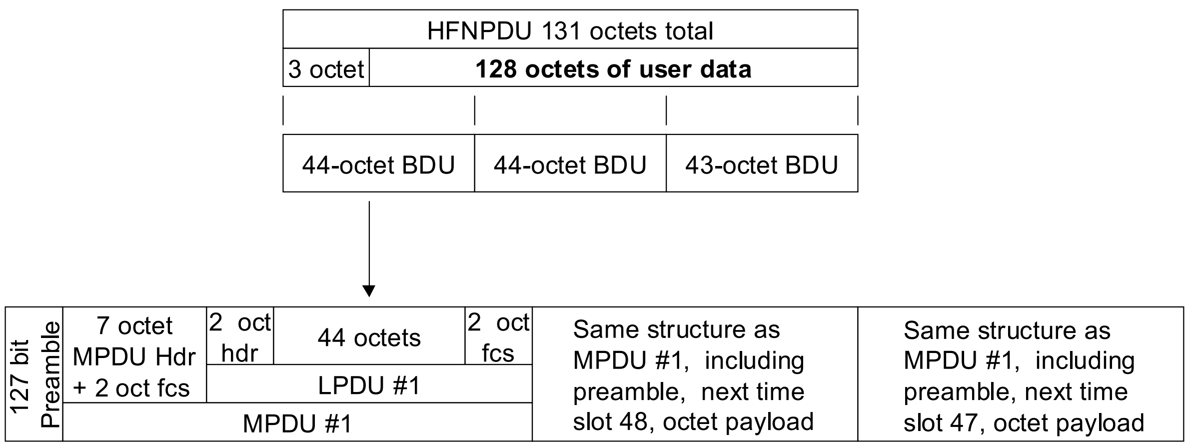


Figure D-2: **Structure of 128-octet User Message on 300 bps HF Data Link Reliable Link Service**

Regardless of which partitioning is used, the receiving subsystem is responsible for checking each received LPDU for errors, requesting that LPDUs received with detected errors or not received be retransmitted, and reassembling the 131 octet HFNPDU containing the 128-octet user data. The HFNPDU is reassembled only after all three LPDUs have been received and pass their respective frame check sequences. Error checking is performed by computing a FCS for each LPDU. If the locally computed FCS does not have a "zero" result, then the received LPDU is discarded and a retransmission is requested.

Reassembly of the HFNPDU starts when all three LPDUs have been received with no detected errors. Reassembly consists of analyzing the two octet header of each LPDU to determine the sequence (order) of reassembly, stripping the two octet header and two octet FCS to recover each BDU, and concatenation of the three BDUs into the 131 octet HFNPDU.

D.2.2 Calculating P_{RA} , and P_0

The reconstructed message is delivered to the HF Data Link user only when a signal is detected, a valid MPDU header is received, and all three LPDUs pass their FCS checks. Assuming that the bit errors are independent for all bits, then these events are all independent as well, because they occur in non-overlapping time intervals. Thus, for the partitioning shown in Figure D-1, the probability that the packet is accepted P_{PA} is

$$P_{PA} = P_D \times P_{MPDU} \times P_{48}^2 \times P_{47} \qquad \text{Eq. [D-1]}$$

where

$P_{PA} = \Pr\{\text{131-octet HFNPDU packet is accepted}\}$
$P_D = \Pr\{\text{MPDU preamble is detected}\}$
$P_{MPDU} = \Pr\{\text{MPDU is accepted}\}$
$P_{48} = \Pr\{\text{48 octet LPDU is accepted}\}$
$P_{47} = \Pr\{\text{47 octet LPDUis accepted}\}$

For the partitioning of Figure D-2, P_{PA} is

$$P_{PA} = (P_D P_{MPDU} P_{48})^2 \times (P_D P_{MPDU} P_{47}) \qquad \text{Eq. [D-2]}$$

The analysis that follows consists of calculating the residual error probability, P_{RE} , for a 131 octet HFNPDU from the P_{PA} , as follows

$$P_{RE} = P_{PA} - P_0 \qquad \text{Eq. [D-3]}$$

where P_0 is the probability that there are no errors in the 154 octet MPDU. Thus, P_0 accounts for that proportion of the accepted packets that are correctly received.

D.2.3 Calculating P_D

The first step is computation of the probability of detection, P_D. The probability detection can be expressed as a function of the channel bit error rate and the preamble characteristics. The preamble used by HF Data Link for signal detection consists of a 127-bit sequence. The received sequence is compared with a replica stored by the receiving station. If T or more of the 127 bits in the received preamble match the stored replica, then the receiving station declares that the signal has been received. Otherwise, if the signal-to-noise ratio is so low that fewer than T bits match the stored replica sequence, the packets transmitted in the MPDU are missed. This preamble also protects against false acquisition in the absence of any transmissions. In this case, any 127-bit pattern generated by noise at the receiving end that differs from the replica by T or fewer bits results in a false alarm. Hence the probability of false alarm, P_{FA}, and the probability of preamble detection, P_D, are given by

$$P_{FA} = 2^{-127} \sum_{k=0}^{T} \binom{127}{k}$$

$$P_D = 1 - \sum_{k=T+1}^{127} \binom{127}{k} p^k (1-p)^{127-k} \qquad \text{Eq. [D-4]}$$

where p is the probability of a preamble bit error. The threshold T is a design parameter chosen to minimize the probability of false alarm while achieving a high probability of detection at a target value of p. (Note that when $p = 1/2$, the probability of false alarm and the probability of detection are equal. Hence the target value of p must be less than 1/2.) For example, with $p = 0.25$ and $T = 36$, the probability of false alarm is $P_{FA} = 5.7 \times 10^{-7}$, and the probability of preamble detection is $P_D = 0.835$.

D.2.4 Calculating P_{MPDU}

The second step is computation of the probability of accepting the MPDU header. For the specified 128-octet payload, the MPDU header consists of 11 octets, or 88 bits, of which the last two octets are a 16-bit frame check sequence (FCS). The purpose of this FCS is to detect residual errors that are not corrected by the forward-error-correcting (FEC) coding applied to the transmitted signal. An MPDU header will be accepted as valid in two cases: 1) when there are no residual errors after FEC processing and 2) when there are residual errors that can not be detected by the FCS. We can compute the probability of an accepted MPDU header by means of conditional probabilities:

$$P_{MPDU} = \sum_{k=0}^{N_{MPDU}} \Big[\Pr\{\text{exactly } k \text{ errors in MPDU Header}\} \times \Pr\{\text{MPDU Header accepted} | \text{exactly } k \text{ errors}\} \Big] \qquad \text{Eq. [D-5]}$$

The 16 bit FCS appended to each MPDU and LPDU for error detection is generated using a 16 bit Cyclic Redundancy Check (CRC-16) defined in ICAO Document 9741. This CRC FCS is the same CCITT 16 bit CRC FCS used in the AMSS and VDL systems. Its error detection capabilities have been analyzed extensively in the literature. Using the results given by Tenenbaum [1] and Wicker [2], it can be stated that the probability of undetected error for the CCITT CRC-16 FCS is a function of the number of bits in error in the protected data block, provided that the error block is sufficiently long [1]:

[1] Both Tenenbaum [1] and Wicker [2] give the average probability of accepting a packet corrupted by random errors as 2^{-16}. In Eq. [D-6], this average value has been adjusted upward by a factor of two to account for the ability of the CCITT-CRC to detect all odd errors. Because half of the errors are odd and are detected, the average probability of accepting a packet with an even number of errors must be twice the average of accepting any number of errors.

$$\Pr\{\text{block is accepted} \mid \text{exactly } k \text{ errors}\} = \begin{cases} 1 & \text{if } k = 0 \text{ (i.e., no errors)} \\ 0 & \text{if } k = 1,\ 2, \text{ or odd} \\ 0 & \text{if } k < 17 \text{ in a single burst of length 16 or less} \\ 2^{-15} & \text{otherwise} \end{cases} \qquad \text{Eq. [D-6]}$$

It is well known that the Viterbi decoders used to provide maximum likelihood estimates of the message bits from convolutionally encoded transmissions produce bit errors that are not independent, but appear in bursts. Extrapolation of the results in [3] indicates that for the signal-to-noise ratios supported in the HF Link Budget (Appendix B), the 90th percentile duration of such bursts is on the order of the constraint length of the encoder, and, therefore, well within the burst detection capability of the CRC. Nevertheless, to ensure that this analysis remains a conservative estimate of the HF Data Link integrity, the analysis assumes that the CRC has *no* burst detection capability, other than that implied by the second and fourth terms of Eq. [D-6].

With this provision, substituting Eq. [D-6] in Eq. [D-5], and setting the block length, K, to the length of the MPDU, N_{MPDU}

$$\begin{aligned} P_{MPDU} < {} & \Pr\{\text{no errors in } N_{MPDU}\} + \\ & \sum_{k=1}^{2} \Pr\{\text{exactly } k \text{ errors in MPDU Header}\} \times 0 + \\ & \sum_{k=3,5,7\ldots}^{N_{MPDU}} \Pr\{\text{exactly } k \text{ errors in MPDU Header}\} \times 0 + \\ & \sum_{k=4,6,8\ldots}^{N_{MPDU}} \Pr\{\text{exactly } k \text{ errors in MPDU Header}\} \times (2^{-15}) \end{aligned} \qquad \text{Eq. [D-7]}$$

The first term on the right-hand side of Eq. [D-7] is the desired term, i.e., error-free reception. The second term accounts for detection of all single and double errors. The third term accounts for detection of all odd numbers of errors. Finally, the fourth term accounts for all even errors more than two, regardless of the burst nature. Eq. [D-7] takes the form of an upper bound, because it does not include an explicit term for the detection of burst errors. Because burst errors are not detected (by assumption, while they are in fact) the analysis proceeds under the assumption that the bit errors are independent with probability p

$$P_{MPDU} < (1-p)^{N_{MPDU}} + 2^{-15} \times \sum_{k=2,4,6,\ldots}^{N_{MPDU}} \binom{N_{MPDU}}{k} p^k (1-p)^{N_{MPDU}-k} \qquad \text{Eq. [D-8]}$$

where N_{MPDU} is either 88 bits or 72 bits, depending on whether the analysis is for Figure D-1 or Figure D-2

D.2.5 Calculating P_{48} and P_{47}

The same techniques can be applied to the calculation of P_{48} and P_{47}. The 48 and 47 octet LPDUs contain 384 bits and 376 bits, respectively. Therefore, we can apply appropriately modified versions of Eq. [D-5], Eq [D-6], and Eq. [D-7] to compute the desired probabilities

$$P_{48} < (1-p)^{384} + 2^{-15} \times \sum_{k=4,6,8...}^{384} \binom{384}{k} p^k (1-p)^{384-k} \qquad \text{Eq. [D-9]}$$

$$P_{47} < (1-p)^{376} + 2^{-15} \times \sum_{k=4,6,8...}^{376} \binom{376}{k} p^k (1-p)^{376-k} \qquad \text{Eq. [D-10]}$$

As before, the first term in Eq. [D-9] and Eq. [D-10] corresponds to correct reception. The second term corresponds to undetected errors on even numbers of bits greater than two. The values of P_D, P_{MPDU}, P_{48}, and P_{47} are plotted as a function of the average corrected (i.e. after FEC decoding) bit error rate in Figure D-3.

D.2.6 Calculating the Residual Error Probability, P_{RE}

The residual error probability, P_{RE}, can now be computed by applying Eq. [D-1] and Eq. [D-3]. The value of P_0 for use in Eq. [D-3] is given by

$$P_0 = (1-p)^{(11+2\times48+47)\times8} = (1-p)^{1232} \qquad \text{Eq. [D-11]}$$

for the single MPDU partitioning of Figure D-1, and

$$P_0 = (1-p)^{(2\times(384+88)+(376+72))} = (1-p)^{1392} \qquad \text{Eq. [D-12]}$$

for the multi-MPDU partitioning of Figure D-2. The results are shown as a function of bit error rate in Figure D-4 and Figure D-5. For the single-MPDU case, the maximum value of P_{RE} is 1.7×10^{-7}, for the multi-MPDU case, the maximum is 1×10^{-7}. In both cases, the maximum occurs in the region where the average corrected bit error rate is relatively small. In this region, the Viterbi decoder bursts are generally short and well within the burst error detection capability of the FCS. Furthermore, this analysis does not take into account other "consistency checks" that must be satisfied during reconstruction of the HFNPDU. Therefore, these predictions are upper bounds on the value of P_{RE}.

This analysis is *conservative*, that is, the true value of P_{RE} is likely to be *smaller* than the prediction, due to the facts that erroneous data must still pass consistency checks during the reconstruction of the HFNPDU and that the burst error detection capabilities of the FCS have not been included in the analysis.

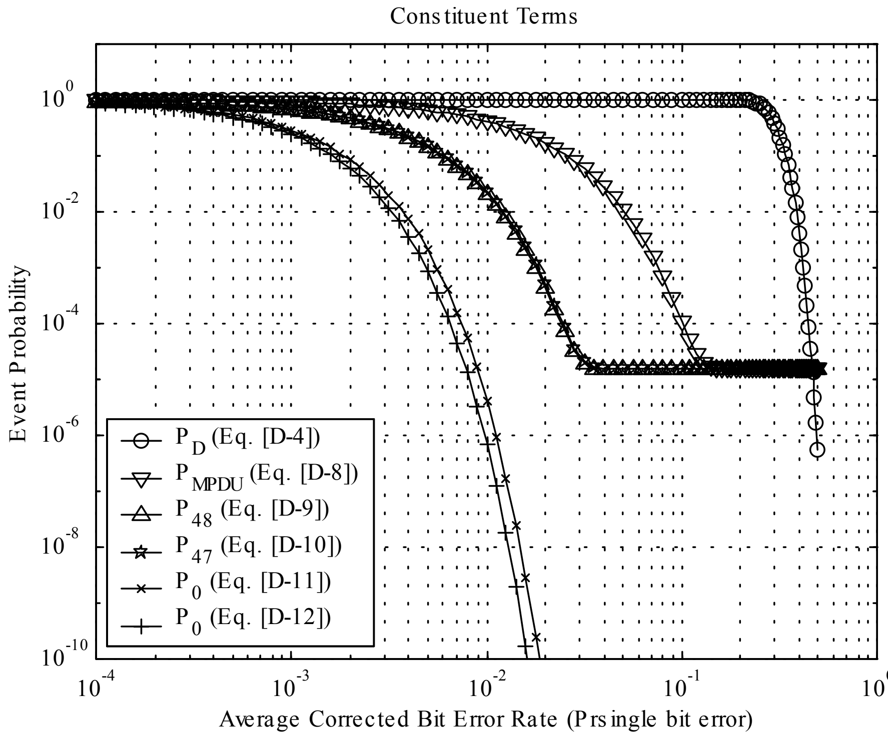


Figure D-3: Values of terms in P_{PA}

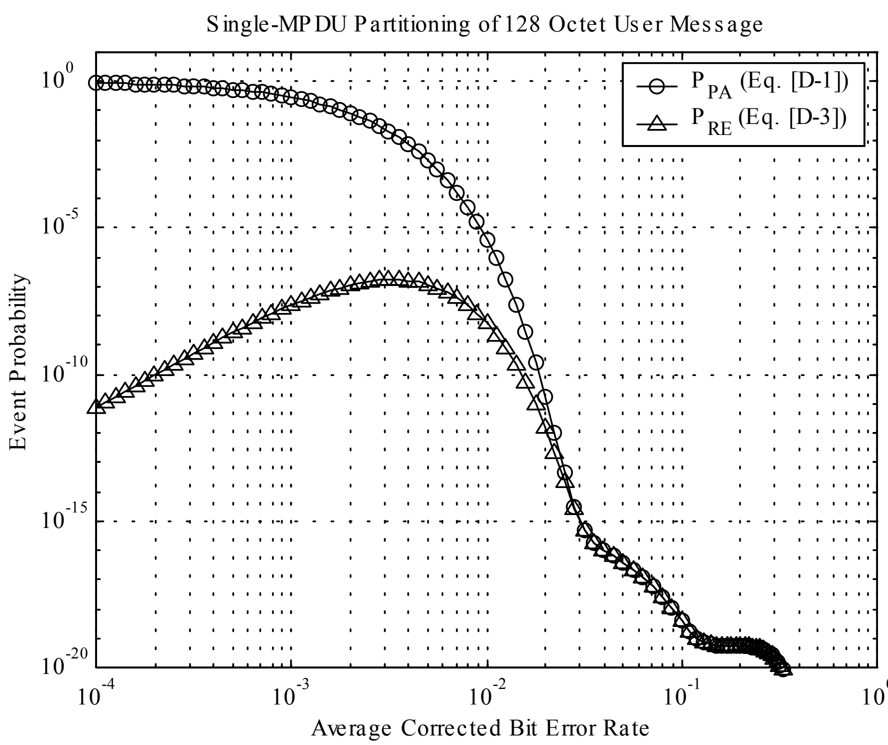


Figure D-4: PPA and P_{RE} for 128-octet User Data Packet on HF Data Link with Single MPDU Partitioning

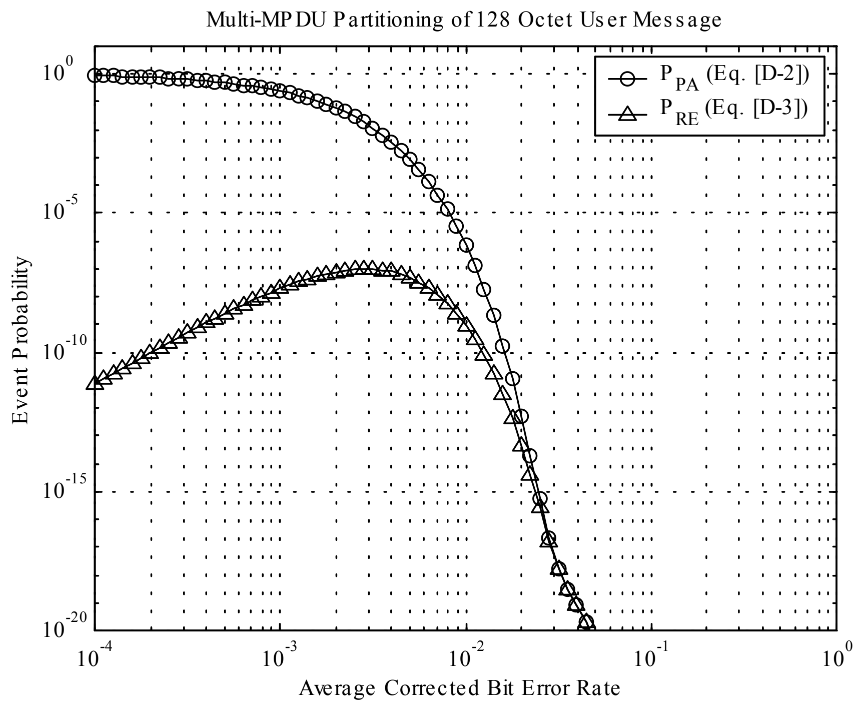


Figure D-5: P_{PA} and P_{RE} for 128-octet User Data Packet on HF Data Link with Multi-MPDU Partitioning

D.2.7 Altenative Partitionings

ICAO Document 9741 allows partitioning into LPDUs with lengths other than the 48-48-47 partitioning assumed for the preceding analysis. One other frequently used partitioning is 57-57-29, which results in two maximum-length (57 octet) LPDUs. Once the appropriate changes to the limits of summation are made, the mathematics of the analysis for the 57-57-29 partitioning is identical to that presented for the 48-48-47 case. The result is a maximum value for P_{RE} of 2.46×10^{-7} for the single-MPDU partitioning and 1.42×10^{-7} for the multi-MPDU case. These values are about 50% larger than the results for the 48-48-47 partitioning, but still well within the MASPS requirement.

It is also possible that the HFNPDU could be partitioned into a multiplicity of relatively short LPDUs. Because each LPDU has an associated 16-bit FCS, such a partitioning would increase the number of FCS bits in the HFNPDU. Increasing the number of FCS bits has the effect of increasing the "minimum Hamming distance" of the resultant code words, and, therefore, *increases* the overall error detection capability within the HFNPDU (see [2]). An increase in the error detection capability *decreases* the probability of residual error below the values computed for the 48-48-47 and 57-57-29 partitions considered earlier.

REFERENCES

[1] A. Tenenbaum, *Computer Networks*, 3rd ed. Upper Saddle River, NJ: Prentice Hall, 1996.

[2] S. Wicker, *Error Control Systems for Digital Communication and Storage*. Upper Saddle River, NJ, 1994.

[3] J. M. Morris, "Burst Error Statistics of Simulated Viterbi Decoded BPSK on Fading and Scintillating Channels," *IEEE Transactions on Communications*, vol. Vol. 40, No. 1, pp. 34-41, January 1992.

This page intentionally left blank.

Appendix E

MINIMUM TRAFFIC MODEL
(FOR OCEANIC AND REMOTE AREAS)

(NORMATIVE)

This page intentionally left blank.

Appendix E— Minimum Traffic Model
(For Oceanic and Remote Areas)
(Normative)

E.1 Introduction

The Traffic Model defined in this appendix was developed jointly by RTCA SC-165 Working Group 3 (AMSS Systems Service and Criteria) and the AEEC HF Data Link Subcommittee. It was intended to define the minimum data link traffic expected to be generated and received by an aircraft during a single flight segment in oceanic and remote areas airspace, considering a mixture of ATC and AOC (safety) messages. A segment duration under these conditions could range to 15 hours.

As the HF Data Link system (as contrasted with the AMSS/AMS(R)S systems) does not support AAC and APC non-safety traffic, appropriate adjustments have been made to the model. Certain message types not applicable to an HF Data Link traffic model were removed; however; their designations were retained in order to maintain compatibility with any earlier analyses or simulations.

It is emphasized that the Traffic Model defined in this appendix is the minimum to be expected under the defined conditions, in the least-demanding type of airspace. Operations in other types of airspace are expected to exhibit a greater demand for communications usage.

E.2 Discussion

The minimum traffic model is shown in Table E-1 and Table E-2. Each type of message is defined and identified, so that message types that may be inappropriate for a given situation can be omitted. Each message type is further described in terms of its message length, priority level and inter-arrival time, with notes as needed to define any additional characteristics. An example of the last, which would be important in a traffic simulation model, can be seen in Table E-1 for the UP3 type message which is expected to follow a DN5 type message (Table E-2). In this case, a DN5 message represents an aircraft's request for AOC information, and the UP3 message represents the ground-side response as occurring some time later in accordance with an exponential distribution having a mean of 60 seconds.

In addition to the specific message types, the traffic model assumes a general level of "background" traffic of undefined applications, but with a defined traffic characteristics and mixture of priority levels. The background traffic is represented in Table E-1 and Table E-2 as types UP8 and DN9. Table E-1 and Table E-2 use the following mappings to the priority levels identified in Section 2.2.4.1: ATC=Flight Safety, AOC=Other Safety. For each specific system to be characterized by this MASPS, additional traffic may need to be included in the RF path traffic model to represent internal signaling and system management traffic in accordance with Section 2.2.5.1.1 and Section 2.2.5.1.2.

In all cases in Table E-1 and Table E-2, the message length is expressed in terms of the originating end system (*i.e.,* at Point A or Point E of Figure 1.2). However, this MASPS defines only the behavior of the air/ground communications system between Points B and C of Figure 1.2. Consequently, it is necessary to convert the input message traffic existing at Points A and E (as defined in Table E-1 and Table E-2) into equivalent data blocks entering Points B and C. The segmentation and overhead data added by intervening subnetworks of course will vary among differing data link environments (see Section 1.5). If the effects of the environments in which a specific HFDL data subnetwork operates are not known, it is acceptable to use the assumptions contained in Table E-3.

Table E-3 provides guidance for the actual traffic presented to Point B (downlink) or Point C (uplink) for each message type, by applying assumptions for the overhead and segmentation that will occur in each data link environment. However, segmentation at the Point B and Point C interfaces has been ignored because of the many possible variants; when this effect is known, it should be included. Where distributions of message sets are required, it is recommended that the traffic generator perform the segmentation/overhead calculation for each individually generated sample application message.

Particular attention should be paid to the additional traffic imposed on the air/ground subnetwork by external network management functions; *e.g.*, the Inter-Domain Routing Protocol of ATN. Such functions may generate a significant traffic load and is not included in Table E-3.

E.3 Segmentation and Overhead Approximations:

ACARS/622:

$$\mathrm{TfcLoad} = 2 \cdot \mathrm{MsgLen} + 37 + 25 \cdot \mathrm{ceiling}\left[\frac{2 \cdot \mathrm{MsgLen} + 37}{214}\right] \text{ octets} \qquad \text{[E-1]}$$

ACARS:

$$\mathrm{TfcLoad} = \mathrm{MsgLen} + 1 + 25 \cdot \mathrm{ceiling}\left[\frac{\mathrm{MsgLen} + 1}{214}\right] \text{ octets} \qquad \text{[E-2]}$$

ATN:

$$\mathrm{TfcLoad} = \mathrm{MsgLen} + 19 \text{ octets} \qquad \text{[E-3]}$$

where:

TfcLoad = traffic load presented to HFDL subnetwork by a message type

MsgLen = end-user message length, from Table E-1 or Table E-2 (octets)

ceiling[ ] returns the smallest integer greater than or equal to its argument.

Table E-1: Minimum Uplink Data Traffic Model (To-Aircraft)

Type	Category	Description	Message Length (octets)	Interarrival time (minutes mean)	Priority (or % Mix)	Notes
UP1	ATC	Alt Assignment + Crossing Restriction + Report Reaching	16	60	ATC	1, 6
UP2	ATC	DARPS Route Clearance, 15 WPs	194	480	ATC	1, 6
UP3	AOC	Various	128 mean	30	not-ATC	2, 3, 6
UP4-UP7	(N/A)	(N/A)	(N/A)	(N/A)	(N/A)	(N/A)
UP8	(all)	Background traffic	exp. distrib, 160 mean	(Note 4)	2/23/75	4, 5

Notes:

1. *UP1 & UP2 follow a DN1 by 30 sec. mean, exponential distribution; and precede a DN2 by 30 sec. mean, exponential distribution.*
2. *UP3 follows a DN5 by 60 sec mean, exponential distribution.*
3. *These AOC messages are generated in a Gaussian process having a mean of 128 octets, σ=242, then truncated for a minimum of 1 octet. The resultant distribution has a mean of 248 octets.*
4. *UP8 traffic to be adjusted (by scaling interarrival time) to be 16% of the total UP1-UP7 traffic.*
5. *Priority mix read as percentages, Urgent/Flight Safety/Other Safety, of background total load. Of these, Urgent and Flight Safety messages are bit-oriented.*
6. *In terms of the safety communications priorities identified in the HF Data Link MASPS, Section 2.2.4.1, ATC=Flight Safety and AOC=Other Safety.*

Table E-2: Minimum Downlink Data Traffic Model (From-Aircraft)

Type	Category	Description	Message Length (octets)	Interarrival time (minutes mean)	Priority (or % Mix)	Notes
DN1	ATC	Request	23	53.3	ATC	1, 9
DN2	ATC	Wilco	3	53.3	ATC	2, 9
DN3	ATC	ADS = Basic + Earth Ref.	17	15	ATC	3, 9
DN4	ATC	ADS = Basic + Earth Ref + Met	22	60	ATC	3, 9
DN5	AOC	Various	50 mean	30	not-ATC	8, 9
DN6-DN8	(N/A)	(N/A)	(N/A)	(N/A)	(N/A)	(N/A)
DN9	(all)	Background traffic	exp. distrib., 160 mean	(Note 5)	2/23/75	5, 6

Notes:
1. *DN1 precedes UP1 and UP2 by 30 sec mean, exponential distribution.*
2. *DN2 follows UP1 and UP2 by 30 sec mean, exponential distribution.*
3. *Every fourth ADS report is a DN4; others are DN3's.*
4. *(Reserved)*
5. *DN9 traffic to be adjusted (by scaling interarrival time) to be 16% of the total DN1-DN8 traffic.*
6. *Priority mix to be read as percentages, Urgent/Flight Safety/Other Safety, of background total load. Of these, Urgent and Flight Safety messages are bit-oriented; Other Safety messages are character-oriented.*
7. *(Reserved)*
8. *These AOC messages are generated in a Gaussian process having a mean of 50 octets, σ=283, then truncated for a minimum of 1 octet. The resultant distribution has a mean of 245 octets.*
9. *In terms of the safety communications priorities identified in HF Data Link MASPS, Section 2.2.4.1, ATC=Flight Safety and AOC=Other Safety*

Table E-3 Assumed Data Block Characteristics Corresponding to Traffic Types

Message Type	Point B/C Data Block Length (octets)	
	ATN Environment	FANS 1/A Environment
UP1	35	94
UP2	213	475
UP3	per Table E-1, + 19 octets per message	Eq. E-2
UP4-UP7	(N/A)	(N/A)
UP8	per Table E-1, + 19 octets per message	Eq. E-1 for bit-oriented Eq. E-2 for character-oriented
DN1	42	108
DN2	22	68
DN3	36	96
DN4	41	106
DN5	per Table E-2, + 19 octets per message	Eq. E-2
DN6-DN8	(N/A)	(N/A)
DN9	per Table E-2, + 19 octets per message	Eq. E-1 for bit-oriented Eq. E-2 for character-oriented

This page intentionally left blank.

Appendix F

OVERVIEW OF THE HF DATA LINK SYSTEM AND ITS ENVIRONMENTS

This page intentionally left blank.

APPENDIX F TABLE OF CONTENTS

This page intentionally left blank.

Appendix F—Overview of the HF Data Link System and Its Environments

F.1 System Elements and Their Functions

The HF Data Link System provides long range communications using HF radio frequency spectrum. HF Data Link is part of an end-to-end communications system used by the air transport industry to exchange Airline Operational Control (AOC) and Air Traffic Services (ATS) messages between aircraft end-systems and corresponding ground-based peers. The Ground Stations (GSs) provide HF-based, air-to-ground digital communications with aircraft via various ground-based computer software applications. Aircraft participating in the system implement the HF Data Link protocols in the avionics. The system provides global coverage for participating aircraft.

The system's architecture is based on the following principles:

- Time Division Multiple Access (TDMA) is used to communicate with multiple aircraft per GS per frequency;
- Multiple GSs are used for coverage within each region;
- Multiple frequencies are used at each GS to compensate for propagation conditions;
- Aircraft may operate independently at one of four data rates: 300, 600, 1200, and 1800 bits/second of user data.; and
- Forward error correction and interleaving are included in the protocol to increase chances of correct first-time receipt of each message block.

HF Data Link uses the High Frequency (HF) radio communications spectrum between 2 and 30 MHz as the data transmission media. Since HF propagation depends upon the reflection of radio waves from ionized layers in the Earth's atmosphere, communication performance is a function of path geometry, ionospheric properties, noise and interference. These aspects of HF communication performance vary with time and geographic location. Successful communication depends on propagation efficiency sufficient to overcome noise and interference on a given frequency and path to provide a Signal to Noise Ratio (SNR) consistent with a designated data rate and specified transmitter/receiver combination.

Establishing an HF Data Link session between an aircraft and a ground station requires the selection of a frequency which is currently exhibiting good propagation characteristics in the area where the aircraft is located. A number of HF propagation conditions must be dealt with in assuring adequate performance for Air Traffic Service (ATS) use. These conditions include the following:

- Frequency changes to account for the variability of propagation conditions,
- Ionospheric storms and cyclic sunspots interrupting communications,
- Large numbers of possible propagation paths dispersing the signal over time,
- Large and rapid fluctuations in phase,
- High interference levels,
- Frequency distortion of wideband signals,
- Lower frequency groups are best for short range and at night, and
- Frequencies above 11 MHz are more useful for long-range daylight communications.

The system uses path diversity and frequency management to address these factors and enhance system availability. Analyses have shown that three or four ground stations, strategically sited in a given geographic region (e.g., North Atlantic, Pacific), and operating at frequencies in the HF aeronautical mobile band can provide high availability.

HF propagation characteristics often require the Ground Station to switch among available frequencies to maintain the best radio-frequency path. An Active Frequency Table (AFT) is used to control which frequency is in use at any location. The AFT is updated as needed using real time data as well as data generated by HF propagation modeling tools. HF propagation is highly dependent on solar activity and, as a result of changing solar activity, the AFT must be updated as required to ensure the system is propagating on optimum frequencies. During normal operations, the AFT is updated on a weekly basis.

The HF Data Link System Table is a file used by the GS to broadcast system information to equipped aircraft. The system table contains a listing of Ground Stations and locations and the frequencies assigned to each GS. The avionics use these data to search for and log-on to an frequency containing an HF Data Link signal. The system table is updated only when a new GS and/or new frequencies are added to the infrastructure.

F.1.1 Ground Station (GS)

A Ground Station provides connectivity between the ground network and aircraft via the RF links. The components of the GS consist of transmitters, receivers, antenna(s) and the GS hardware and software necessary to perform the functions of interfacing between the ground network and the Aircraft Station (AS).

F.1.1.1 Aircraft Station (AS)

An Aircraft Station (AS) provides connectivity between the aircraft's data and/or voice networks via the RF links for transmission and reception. The components of the AS consist of transceivers(s), antenna(s) and equipment and software necessary to perform the functions of interfacing with the RF paths(s) to/from the Ground Station (GS) and provides baseband packet-mode interfaces at the Subnetwork Layer with other avionics equipment. The operational characteristics and requirements for the AS are described in the Minimum Operational Performance Standards (MOPS); e.g., RTCA DO-265 for HF Data Link system.

F.1.1.2 Network Control and Coordination Function

The Network Control and Coordination Function performs administrative and technical management functions for the HF Data Link system. Monitoring the operational aspects of the system, outage and maintenance tracking as well as performance management.

F.2 End-to-End Communications Environment

F.2.1 End-to-End Data Link

Aeronautical data links can be supported by several existing and potential future media of air-ground communications, of which HF Data Link is one. Effective utilization of data link technology for ATS and AOC purposes requires a uniform, universally defined and implemented set of protocols. The concept of the future Aeronautical Telecommunications Network (ATN) embodies that objective, through the establishment of and end-through-end Packet-mode data network architecture having common access procedures independent of the air-ground communications medium. Existing air-ground data link architectures, exemplified by Aircraft Communications and Reporting System (ACARS), utilize procedures that are specific to their individual architectures, but have the advantage of widespread implementation in aircraft and ground systems.

F.2.2 The Aeronautical Telecommunication Network

The ATN architecture is predicated on data communications standards developed by the International Organization for Standardization (ISO) which apply the principles of the Open System Interconnect (OSI) model. High-level requirements for the ATN have been published by ICAO as SARPs; updates are in progress and can be expected.

It is assumed that characteristics of the HF Data Link subnetwork and in particular the AS and GS interfaces, have been defined and designed in anticipation of integration as an ATN subnetwork, in accordance with relevant ICAO SARPs.

F.2.3 FANS 1/A Data Link

FANS 1/A data links utilize ACARS, originally a VHF data link system developed by the commercial air carrier industry that has grown to a system of global dimension since its introduction in the late 1970's. ACARS has been modified to use not only VHF but also AMS(R)S and HF Data Link. Currently, over 6000 aircraft are fitted with ACARS VHF equipment, including communication management units capable of supporting data link operation and their interfaces with other avionics equipment (*e.g.*, flight management computers). Consequently, all aircraft fitted to date with HF Data Link capability utilize the ACARS management units and supporting ground infrastructure available through service providers.

ACARS is defined in Airlines Electronic Engineering Committee (AEEC) documentation. A basic end-through-end ACARS data link does not support bit-oriented protocols, user data transparency (*e.g.*, bit-oriented data), or end-through-end error protection; hence, it is of limited use for ATS message service. Consequently, mechanisms have been developed to overcome these limitations, and are documented in ARINC Specification 622 which specifies a protocol overlay on the ACARS character-oriented system. These mechanisms are implemented in end systems to encode bit-oriented data in such a way as to allow the character-oriented ACARS subnetworks to transport data transparently, and incorporate an end-through-end cyclic redundancy check (CRC) of message integrity. In order to ensure the integrity of the information, the ARINC 622 ACARS convergence function and the applications it supports must be hosted together in an avionics end-system that can be certified for the required level of integrity. The end-system may be an ACARS peripheral (*e.g.*, FMS, ADSU) which routes air/ground messages via an ACARS Management Unit (MU), an ACARS MU itself, or an integrated unit typical of next generation avionics.

An ACARS air/ground subnetwork does not support priority distinctions among messages. However, external entities (*e.g.*, an ACARS MU having multiple data input/output ports can arrange the precedence of messages presented to the air/ground subnetwork for transmission, in accordance with the implied priority level associated with each port. Such an arrangement is incorporated in the architecture of FANS-1/A applications.

FANS 1/A data links implement the mechanisms described above, and have additional features to support certain ATS applications. The environment application interfaces support most ATN-compliant applications by emulating the ISO 8072 Transport Service. The application interface, in effect, provides a convergence function between the connection-oriented ISO 8072 Transport Service Interface and the connectionless ACARS protocol beneath it. However, the underlying ACARS components do not explicitly support message priority. The ACARS/ARINC 622 environment normally interfaces with AESs via a Data-2 avionics interface, described in Section F.3.1.

A FANS-1/A compatible system supports ATS applications through the use of the additional system provisions as follows.

For an ATS transaction to begin, the ATS facility must discover the existence of the aircraft, as well as the identification of the ACARS peripheral or ACARS MU which contains the ATS application(s). Similarly, an aircraft must acquire the ground address of the ATS facility. To do this, a notification function is necessary. This function is defined as an application process, ATS Facilities Notification (AFN) which resides in the aircraft within the aircraft end-system and on the ground in the ATS facility. The AFN provides an automated mechanism to perform notification, and exchange of end-system addresses and capabilities.

Once the ATS facility has been notified of an aircraft's readiness for data communication and both end-systems have acquired the necessary addresses, end-through-end application communication can begin. At the transmitting end-system, an ATS message is created by the appropriate ATS application. The air/ground message is first processed by calculating a CRC which is appended to the application data. Next, the CRC and any bit-oriented application data are processed through a bit-to-hex conversion algorithm. Then the converted string is formatted using the rules of ARINC Specification 622.

At the receiving end-system, the character string is extracted from the ACARS message according to ARINC Specification 622. The CRC and any data from bit-oriented applications are processed through a hex-to-bit restoration algorithm. The resulting message contains both application data and the associated CRC value. The receiving end-system is responsible for evaluating the CRC.

F.3 Transceiver Avionics Interface Modes

"Data-2" and "Data-3" define differing avionics interfaces with user avionics onboard aircraft. A communications transceiver such as used by AMSS (packet-mode) and HF Data Link may support either or both interfaces.

F.3.1 Data-2 Interface

Data-2 provides a simple data link interfaces between a transceiver and external user avionics; for example, between and Aircraft Station (AS) and an ACARS Management Unit (MU) via an ARINC 429 link interface protocol. In such a case, an appropriately-formatted ACARS data block is passed directly to the transceiver, which provides only link layer and physical layer services. Across the AS-GS link, a Data-2 transmission is identified by a preceding two-octet header (coded as FF_h).

Data-2 is transparent to user data, but supports only a single connection across the transceiver interface and may not support priority and preemption. All data communications via Data-2 are handled by a transceiver at a link-layer priority level of 7, in accordance with the common AMSS and HF Data Link priority structures. Any data passed to a transceiver that does not have a ground connection are discarded.

F.3.2 Data-3 Interface

Data-3 defines the availability of an Aeronautical Telecommunications Network (ATN)-compliant subnetwork protocol in the a transceiver. Data-3 necessarily implies a transceiver architecture having a network layer comprising an ISO 8208 (DCE) Subnetwork Access (SNAc) sublayer, a Subnetwork Dependent Protocol (SNDP) sublayer, and a subnetwork interworking function (IWF) sublayer that provides for the mapping between the first two sublayers. This architecture offers connection-oriented packet data service to the external Higher Layer Entities (HLEs) by establishing subnetwork Switched Virtual Circuits (SVCs) with its peer entity in the GS. It also provides segmentation/reassembly services, full support of priority and preemption, and address conversion between the HLE and the SNDP.

F.4 HF Data Link Performance as a Component of Global CNS/ATM

To support the implementation of the new CNS/ATM framework, the concept has emerged that different levels of overall performance will be required of a CNS system for different flight procedures. The requirements might also vary according to the environment in which a procedure is being performed (*e.g.*, oceanic vs. high-density traffic areas). Further, the performance of each component of a CNS system (communication, navigation and surveillance) could be expressed as individual sets of performance as follows:

- Required Navigation Performance (RNP),
- Required Surveillance Performance (RSP), and
- Required Communications Performance (RCP).

As work in these areas was not mature when this MASPS was produced, the following RCP material is presented as an assumption of a possible outcome based on work to date. The organization and dimensions of the performance requirements in this MASPS have been made consistent with the contents of this section, which are presented here as assumptions.

F.4.1 Assumptions Regarding the RCP Concept

Required Communications Performance (RCP) is a statement of the end-through-end communications performance necessary for flight within a defined airspace, or to perform a discretely defined operation or procedure. RCP is a set of requirements based on the safety objectives needed for a particular operation or procedure, and is independent of the technology or combination of technologies that may be utilized for communications.

When humans are involved (*e.g.*; controller-pilot data link communications), the RCP parameters are based on a "transaction", defined as two-way communication such as a query/response or an instruction/acknowledgment pair. Thus, for example, the RCP end-through-end transfer delay parameter includes the human response time necessary for receiving and comprehending the initial message, determining the response and entering the response.

F.4.2 Required Communications Technical Performance (RCTP)

As outlined above, RCP parameters can include human factors components. Recognizing that technical parameters are needed for the end-to-end communications link itself, another set of parameters called Required Communications Technical Performance

(RCTP) has been defined, for which the human factors of RCP parameters have been removed.

The concept of RCTP includes the following additional sets of performance requirements, which are defined in greater detail below:

- Installed Communications Performance (ICP)
- Actual Communications Performance (ACP).

An inherent benefit of Required Communications Technical Performance is that a communications link may have to meet only the performance parameters required for those procedures it is performing and the environment in which it is operating. This will result in cost savings by reducing the risk of "over-specifying" the requirements for communications systems; and enhance safety by clearly qualifying communications links in common and comparable terms.

F.4.3 Installed Communications Performance (ICP)

At its highest level, ICP is a statement of the nominal performance of a specific communications "string", typically comprising:

- The aircraft end system (terminal equipment),
- aircraft avionics, including radio(s) and antenna(s),
- the RF path,
- ground stations,
- ground-ground distribution networks, and
- ground end system (terminal equipment).

A representative picture of these elements of the communications system serving the end users' terminal equipment is presented in Figure 1-2. The boundaries of the elements, however, may not fall cleanly along the strictly technical subnetwork boundaries as displayed. An important example is the differing institutional boundaries of an aircraft and an air-ground subnetwork provider. The owner or operator of an aircraft is responsible for its equipage, hence its performance; whereas the provider of an air-ground communications service has the responsibility for the performance of that element of the end-through-end link. Different service providers may have differing performance characteristics, which may be differentiated by aircraft equipage and/or service cost factors; and a given service provider may offer different service levels that may be differentiated by cost or other factors. Ultimately, the aircraft owner or operator is responsible for the selection(s) of providers and levels of service as necessary for operational authorization; however, it is the service provider's responsibility to meet the represented performance levels, initially and on a continuing basis.

The ICP_{TOTAL} is determined from an appropriate combination of the ICP_i of each of the i elements comprising the string.

The ICP (and constituent ICP_i's) are expressed in the same terms, and with the same parameters, as is RCP, so that ICP can be compared directly with RCP. For the more stringent levels of RCP it may be necessary to utilize more than one string (including possibly more than one medium or technology), in order to meet the RCP.

The ICP_{TOTAL} for a given aircraft is determined by the combination of its equipage, crew qualifications, the air/ground service arrangements made by the aircraft's owner or operator, and the other elements of the communications "string" identified above including the ground side end system. Most, and perhaps eventually all, of these elemental ICP parameters will be derived from standards document such as this MASPS. The appropriate combination of the elemental ICPs will provide the ICP_{TOTAL}. The ICP_{TOTAL} may be used to evaluate whether or not that aircraft and its supporting ground systems meet a specific RCTP for a given operation or airspace; hence, whether or not it satisfies the RCTP level required for dispatch or initiation of an operation.

F.4.4 Actual Communications Performance (ACP)

Actual Communications Performance is a statement of the near-real-time end-to-end communications capability of the same systems that are characterized in terms of their ICP(s). ACP is expressed using the same parameters as for RCP and ICP, but may differ from the ICP of the communications systems due, for example, to equipment malfunctions or changes in propagation conditions. The operational application of ACP is not yet determined; however, the relationship to the general concept of performance monitoring is clear.

F.5 Installed Communications Performance (ICP) Parameters

The primary RCP, and hence ICP, parameter categories are availability, continuity, delay, and integrity. These are specified in this MASPS for an HF Data Link subnetwork between the reference Points B and Point C in Figure 1-2. As that path includes an AS, the requirements for the subnetwork are determined assuming that the AS meets the requirements of the MOPS (RTCA DO-265) as well as those of this MASPS.

F.5.1 Transfer Delay

Transfer delay requirements are set by the need to assure that data link messages are delivered through the communications system in a timely manner. Tolerable data message transfer delays are determined by their particular application; *e.g.*, ADS reports must be received by the ground automation system within a time period related to the separation assurance criteria in a given airspace or under a particular set of operational procedures.

The measured transfer delay characteristics of a subnetwork and its elements are normally characterized by data which, plotted as a histogram, appear as an probability distribution having a biased offset (latency) from the zero value. This MASPS expresses three different values of transfer delay—the latency, the mean value (transit delay) and the 95th-percentile value. These values are the minimum necessary to combine properly the delay data of individual elements, systems and subnetworks for aggregated delay values (*e.g.*, for "end-through-end" delays).

F.5.2 Integrity

The integrity of HF Data Link communications is measured in terms of data block error rate. The integrity goal is set by the need to assure that errors in data link messages do not compromise the safety of flight.

F.5.3 Availability and Continuity

Availability criteria have parameters that represent the needs for high reliability of safety communications services, and short restoration times in the event of failures. Quantitatively, the requirements for safety communications are more rigorous than are generally accepted for commercial communications.

The parameter Availability Ratio is defined as the ratio of actual operating time to specified operating time, and is normally specified and observed over long periods of time (*e.g.*, one year). Actual operating time herein is taken to be the time during the specified operating time that the system is operating normally (*viz*., delivering its required performance). Unless specifically stated otherwise, specified operating time for HF Data Link is taken to be full clock and calendar time.

Continuity is a parameter related to the short-term performance of a given operation, and is the probability that the system is operating normally during a specified period of time. Once an aircraft has committed to perform a certain operation based on the availability of the necessary communications, there must be a high probability that the communications service will continue to be available throughout the operation. This short-term probability is the continuity of service, and is calculated using terms having metrics of probability and duration of time.

F.5.4 Throughput and Capacity

The capacity required of a communications system is determined primarily by the service provider(s) in considering user traffic models enumerating throughput and delay requirements. Characteristics relating to capacity may be set by design specification, contract or through other service arrangements. Throughput (or traffic loading) requirements are set by the need to assure that each aircraft user and each ground user served by the communications system have the ability to enter and receive the communications traffic necessary for the safe and efficient conduct of flight. From the perspective of an aircraft, this means that the communications link(s) available to the aircraft must have sufficient capacity to transport all expected communications to and from the aircraft while meeting all other RCP requirements. From the perspective of a ground user, this means that the communications system must support the total traffic to and from some expected number of aircraft. From both perspectives, access to additional resources for high-priority traffic in unusually high loading conditions is provided by the priority, precedence and preemption mechanisms implemented in accordance with safety communications requirements.

Data throughput for end users is expressed in terms of generation and reception rates of messages, and the sizes of those messages. For a subnetwork that is part of the end-to-end packet-mode (ATN) data link, throughput is expressed in terms of sizes and rates of packets, or data blocks, entering and leaving the subnetwork.

The combination of delay and throughput capabilities, hence capacity, of a communications system is constrained by economics, and the characteristics and specific design of the transmission medium employed. The delay requirements are established by the set of applications for which the system is used. Therefore, the needed capacity is a function of throughput needs that take into account numerous demand factors such as volume served, number of aircraft served, types of operational procedures supported, frequency and length of communications, etc. These demand factors are subject to considerable variability among various regions, and will vary with time as measured on several scales.

The approach taken in this MASPS is to impose neither total system capacity nor total throughput requirements. Rather, for packet-mode data, a range of delay vs. block length capabilities is displayed for HF Data Link channels under "nominal maximum" loading conditions. These data may be determined for the overall coverage of the system, or for each specific region in accordance with the requirements of Section 2. From these data, useful estimates of the system capacity stated in terms of number of aircraft served for any particular combination of airspace and communications loading.

This page intentionally left blank.

Appendix G

METHODS OF COMBINING AND PARTITIONING ICP FACTOR VALUES

This page intentionally left blank.

APPENDIX G TABLE OF CONTENTS

This page intentionally left blank.

Appendix G —Methods of Combining and Partitioning ICP Factor Values

G.1 Introduction

This MASPS provides methodologies for the rigorous estimation of the Installed Communications Performance (ICP) factor values of an air/ground data link utilizing HF Data Link systems in accordance with the introduction of Section 3. For aggregation, the quantitative values for any particular HF Data Link subnetwork will have to be combined with the values of the other subnetworks that constitute the end-to-end communications link, in order to determine the end-to-end ICP. Conversely, the development of the parametric values for the air/ground subnetwork itself may be accomplished by the appropriate aggregation of values determined for its individual elements. The latter aspect is discussed in the other technical appendices associated with Section 3.

The reverse situation exists when one wishes to partition, say, end-to-end ICP factor values for allocation or allotment to individual elements that constitute that end-to-end link. For either aggregation or partitioning, appropriate combinatorial techniques must be used. In most cases, arithmetic techniques (*e.g.*, addition, subtraction, multiplication, division) can be employed in conjunction with a topographic representation of the networking that makes up the communications link. However, in some cases -- notably, 95^{th} -percentile Transfer Delay -- simple arithmetic can lead to substantial errors. Such errors result in either overstatement of a subnetwork's performance, with a consequent compromise of safety objectives, or an understatement of a subnetwork's performance which could introduce unnecessary costs.

G.2 Combinatorial Methods

Acceptable methods of aggregating, or partitioning, ICP factor values are outlined in this section. In interpreting ICP values that characterize a subnetwork or its elements, it is useful to keep in mind that the values have been determined by simulation, analysis, measurement or a combination of those techniques; hence, they are the result of statistical procedures.

G.3 Availability and Continuity

Methods for aggregating and partitioning Availability and Continuity parameter values are discussed in Appendix C.

G.4 Integrity

An analysis of HF Data Link integrity is contained in Appendix D.

G.5 Transfer Delay

G.5.1 Sources and Manipulation of Transfer Delay Data

The determination of the of the transfer delay characteristics of a subnetwork is perhaps the most problematic of the ICP factors. This is because of the wide ranges of multiple parameters identified in Section 2.2.5.1 that have substantial effects on transfer delay, such as message length, message priority level, channel loading and perhaps differing System Model conditions. It is considered impractical to characterize an air/ground subnetwork

Model conditions. It is considered impractical to characterize an air/ground subnetwork fully under all such conditions, particularly with respect to channel loading. Consequently, it is assumed that the required transfer delay values will, at least initially, be determined by analytical and simulation techniques.

High-fidelity transfer delay simulation data are often collected by capturing the number of occurrences of a particular set of message and system state conditions in multiple bins representing the ranges of the parameters discussed above. An example of a two-dimensional histogram plotted from such data, for 5,000 samples and a bin width of 1 in the

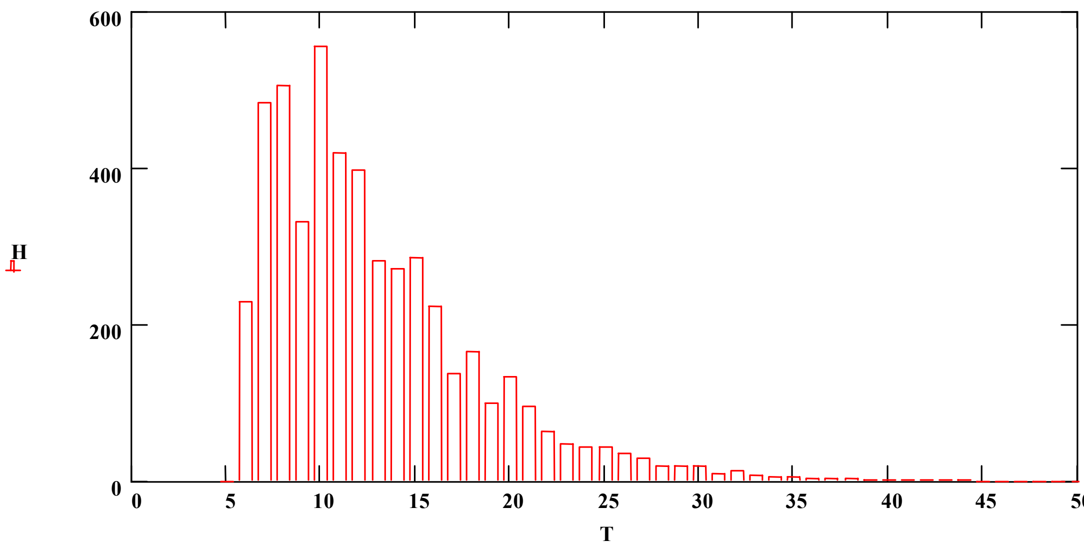


Figure G-1. Representative Histogram of Transfer Delay Data

time dimension, is shown as "H" in Figure G-1. The data represent the transfer delay of a 5,000 data blocks of a particular length and priority level through a subnetwork that is also carrying substantial other traffic. The height of each bar in the figure is the count of the blocks whose delay falls within the width of each bin (in this case, the bin width is 1).

To produce the equivalent of a probability density function, the data must be normalized by the number of samples (in this example, 5,000). From the normalized data distribution, values of the mean and 95th percentile can be calculated using ordinary arithmetic techniques. Direct calculation of other moments of the data set is also possible, and is desirable but not required by this MASPS.

In Figure G-1, it is noted that there are no "hits" in the data bins for a block delay of 5 and below. This is due to the sum of "fixed" delays within the subnetwork or element being simulated (or measured), such as fixed-delay buffering; input, output and internal bandwidths; and propagation delay. Such delay components are invariant for the particular conditions of block length and priority level, etc., set up for the capture of this particular set of data. However, some of the minimum delay components can be expected to vary as a function of block length and priority level, among other possibilities. Consequently, the latency values for a range of data set conditions must be determined in each individual case.

The just-described minimum achievable delay is called Latency, one of the required transfer delay parameters. It is as important to identify a value of latency as it is for the other characterizing values of a data set, precisely because the latency is invariant and must be removed from the mean and 95th -percentile values before they can be used as probability distribution characteristics. Otherwise, any subsequent manipulation of the data set characteristics, such as for aggregation or partitioning, can lead to serious errors as is demonstrated in the following section. In the example of Figure G-1, the value of latency is taken to be 5 as that is the largest bin from zero that contains a zero "hit" count. The latency value of some other data distributions may not be so easily estimated, as the rise from the zero ordinate value may not be so sharp; however, various curve-fitting strategies can be of help.

The minimum required characterization of the data set represented in Figure G-1 is as follows:

Latency	5.00	s	
Mean	13.31	s	(includes Latency)
95^{th} Percentile	23.39	s	(includes Latency)

G.5.2 Analysis by Data Probability Distributions

Ideally, the use of transfer delay data for aggregation or partitioning would be through the application of the actual probability density functions, or good approximations, from which the latency, mean and 95^{th} -percentile values were taken. This is because the 95^{th} percentile cannot be estimated accurately by simple arithmetic. For example, if the 95^{th} percentile values for two subnetworks in series were known, and were simply added to estimate the 95^{th} -percentile transfer delay of the combined subnetworks, the result will underestimate the performance of the combination. The degree of underestimation can be sufficiently great so as to lead to higher overall network costs or to exclude an implementation for certain operations because the ICP/RCP criteria seemingly were not met.

Normally, the actual distributions will not be known, so approximating the available data with a distribution function will be necessary. Numerous techniques can be used for curve fitting. In the case of the Figure G-1 example, the relatively low value of the ratio of the 95^{th} percentile to the mean (about 2.2) suggests that an exponentially-based distribution having a single parametric degree of freedom, which frequently appear in communications work, might be a good fit. Further, as the plotted data set is available in Figure G-1, inspection of its shape suggests a Poisson distribution. In cases where only the parameters values are available, other judgmental factors can be applied in the choice of an appropriate fitting function.

The data of Figure G-1 can be fitted well by a continuous Poisson distribution p(t) expressed as the following probability density function (PDF):

$$p(t) = a^2 \cdot (t-T) \cdot e^{-a \cdot (t-T)} \qquad \text{Eq. [G-1]}$$

where: $t \geq 0$
T = Latency (offset from zero due to invariant delay)
$a = 2/\lambda$
λ is the mean.

Note that in this case it was possible to write the distribution function in such a way as to accommodate directly the latency. The simplest fit can be attempted by directly entering the latency and mean values, then calculating the 95^{th} percentile by solving the associated cumulative distribution function, P(t), for t when P(t) = 0.95:

$$P(t) = \int_0^t p(t)dt \qquad \text{Eq. [G-2]}$$

Calculation of the mean and 95th percentile of the fitted distribution yields the following:

Table G-1. Comparison of Raw Data and Fitted Curve Parameters

	Normalized Histogram	Fitted Continuous Poisson distribution
Latency	5.00	5.00
Mean (no latency)	8.30	8.30
95th Percentile (no latency)	18.87	19.70

The fit is considered to be excellent, with a slightly conservative value for the 95th percentile. A further check can be made by comparison of the plots for p(t) and P(t) overlaying the original histogram and its cumulative normalized representation, H_CDF(T), respectively, as shown in Figure G- 2.

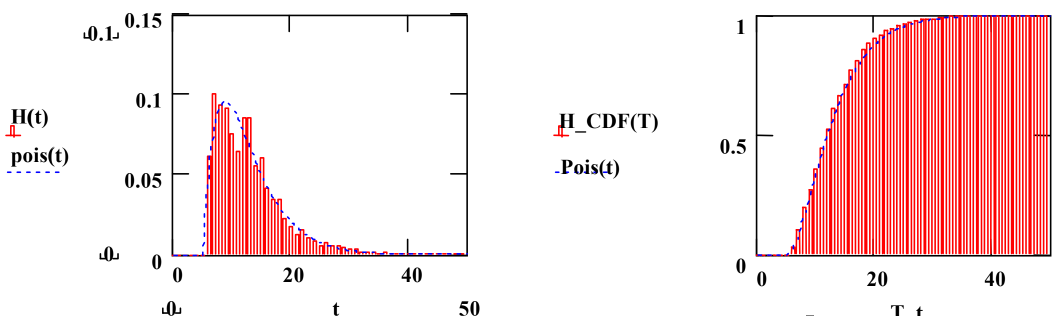


Figure G- 2. Comparison of Normalized Histogram Data and Fitted Distribution; (a) PDF and (b) CDF

Note that, had latency not been separately accounted for by effectively removing it from the data for distribution curve fitting, a significantly poorer fit would have resulted in this example.

Only mean transfer delays and latencies can be simply summed. However, average delay is considered to be less meaningful to safety applications than the 95th percentile of the system's transfer delay. For combining the delays of serial elements, it is necessary to convolve their individual distributions, each normalized by subtracting the value of its latency component. As latencies are irreducible delays, they can be separately subtracted or added from the mean and 95th -percentile values for normalization and reconstitution purposes, respectively. Reconstitution of the aggregated distribution is accomplished by adding the latencies of the two elemental distributions to the mean and 95th -percentile values of the distribution obtained from the convolution.

Convolution is a standard mathematical operation performed using the following integral:

$$\int_0^{\tau} p_1(t) \cdot p_2(t-\tau)\, d\tau \qquad \text{Eq. [G- 3]}$$

where: p1(t) = the PDF describing one element
p2(t) = the PDF describing the other element.

For multiple elements, the convolution process is repeated on a pair-wise basis using Eq. [G-3]. Valid, continuous distribution functions representing the delay data are required; calculation of the convolution integral is not readily performed without specialized program tools; and even fast computers need substantial computation time for the more complex distribution functions.

G.5.3 An Approximation Technique for Aggregation and Partitioning of Transfer Delay Data

If only the three-parameter transfer delay data required by this MASPS are available, a simple arithmetic approximation for manipulating 95th -percentile transfer delay data is desirable. As discussed above, simple addition and subtraction consistently under-estimates the performance. Another suggested method has been to calculate the square root of the sum of the squares of values (root-sum-square method); however, this method generally results in over-estimation of the performance. The consequences of such errors are illustrated in Section G.6.

A combination of the two methods, given in Eq. [G- 4] below, has been investigated.

$$P_{TOTAL}(95) = \frac{P_1(95) + P_2(95) + \sqrt{P_1(95)^2 + P_2(95)^2}}{2} \qquad \text{Eq. [G- 4]}$$

where: $P_{TOTAL}(95)$ is the estimated 95th -percentile value of the result
$P_1(95)$ = the 95th -percentile value of one element
$P_2(95)$ = the 95th -percentile value of the other element

Eq. [G- 4] has been compared with the actual convolutions of PDFs and solutions for resulting 95th -percentile values under a range of PDF forms and distribution parameters. The results are displayed in Table G- 2, in which all distribution moments are normalized for zero latency. In all cases, the estimation algorithm produces a reasonable approximation to the true values, with a consistent error on the positive (conservative) side.

As with convolution, applying the approximation of Eq. [G- 4] requires normalization; however, as the Eq. [G- 4] operation involves only the 95th -percentile values, only they need to be normalized. by subtraction of the latency component. It is to be noted in Table G- 2 that the mean values of the convolved result are equal to the sum of the individual distribution means values.

Table G- 2. Comparison of Combining Algorithm with True Convolved Values

Distri-butions	P_1(mean)	P_1(95)	P_2(mean)	P_2(95)	Conv Mean	Conv95	P_{TOTAL}(95)	P(95) Error
A	1.50	3.91	1.50	3.91	3.00	6.30	6.67	6%
A	6.30	3.91	4.50	8.460	6.00	10.51	10.84	3%
B	8.00	24.00	8.00	24.00	16.00	37.99	40.97	8%
B	8.00	32.00	8.00	32.00	16.00	50.16	54.63	9%
B	8.00	40.00	8.00	40.00	16.00	63.95	68.28	7%
B	32.00	160.00	32.00	160.00	64.00	255.81	273.14	7%
B	32.00	96.00	32.00	96.00	64.00	161.00	163.88	1%
C	9.09	21.56	18.18	43.13	27.27	54.47	56.45	4%
C	9.09	21.56	9.09	21.56	18.18	35.24	36.81	4%
C	18.18	43.13	18.18	43.13	36.36	70.49	73.62	4%
D	0.50	1.50	0.50	1.50	1.00	2.37	2.56	8%
D	0.50	1.50	1.00	3.00	1.50	3.68	3.92	7%
D	0.50	1.50	2.00	5.99	2.50	6.57	6.83	4%
D	2.00	5.99	2.00	5.99	4.00	9.49	10.23	8%
D	2.00	5.99	6.00	17.97	8.00	20.41	21.46	5%
E	2.00	5.99	2.00	4.74	4.00	8.69	9.19	6%
E	2.00	5.99	4.00	9.49	6.00	12.59	13.35	6%
E	6.00	17.97	18.00	42.70	24.00	50.83	53.50	5%

Distributions:

A = Gamma Distributions, 1 degree of freedom
B = Gamma Distributions, 2 degrees of freedom
C = Continuous Poisson Distributions
D = Exponential Distributions
E = Continuous Poisson Distribution and Exponential Distribution

The complete process of the approximation is as follows:

1. Subtract the respective latency value from the 95th-percentile value of each elemental distribution,
2. Calculate $P_{TOTAL}(95)$ by applying Eq. [G- 4] to the normalized 95th-percentile values from Step 1,
3. Add the sum of the elemental latency values to $P_{TOTAL}(95)$ to obtain the approximate 95th-percentile value of a convolution result,
4. Add the sum of the elemental latency and mean values to obtain the mean of value of a convolution result, and
5. Add the sum of the elemental latency values to obtain the latency value of a convolution result.

G.6 Illustrations of Transfer Delay Partitioning by Various Methods

This section illustrates the magnitude of errors that can arise through application of simple arithmetic in the partitioning of transfer delay values, and the utility of the approximation of convolution presented in Section G.5.3. Also illustrated is the utility of the required Section 2.2.5.1.4 methodology for transfer delay declarations, particularly in terms of transfer delay vs. message length characteristics. For these purposes, reference is made to guidance on transfer delay characteristics of an end-to-end communications link utilizing an HF Data Link system conforming to SARPs Chapter 11, in Reference [G- 1].

G.7 Aggregation

An illustration of the magnitude of errors produced by simple addition of 95th -percentile transfer delay values can be derived directly from the data of Table G- 2. For each case displayed each row, addition of the 95th -percentile values produces the following results:

Distribution	Combined P_{95} by Convolution	Combined P_{95} by Summation	P_{95} Error by Summation
A	6.3	7.8	+24%
A	10.5	12.4	+18%
B	38.0	48.0	+26%
B	50.2	64.0	+28%
B	64.0	80.0	+25%
B	255.8	320.0	+25%
B	161.0	192.0	+19%
C	54.5	64.7	+19%
C	35.2	43.1	+22%
C	70.5	86.3	+22%
D	2.4	3.0	+27%
D	3.7	4.5	+22%
D	6.6	7.5	+14%
D	9.5	12.0	+26%
D	20.4	24.0	+17%
E	8.7	10.7	+23%
E	12.6	15.5	+23%
E	50.8	60.7	+19%

A significant error in the aggregation of 95th -percentile delays is seen when estimated by simple summation, as compared with the correct result obtained by convolution. If further aggregation of similar values by addition were to continue for other elements in the communications chain, the resultant error could be quite gross. The magnitude of error by addition is reduced under conditions where the elemental values differ greatly. Also, because latency values do add directly, the errors by addition are reduced where the individual latency values are significant components of the delay values.

G.8 Partitioning for Allocation and Allotment

For the illustrations of the consequences of errors of using an inappropriate methodology for purposes of allocation, it is assumed that the requirements for a particular operation in an Oceanic FIR include a 200-second end-to-end 95th -percentile transfer delay for all transactions; and that the allocation policy allots equal delay between pair-wise elements of the end-to-end link when their characteristics are not known.

Case 1 -- Simplistic Approach

Step 1: In an analytical regimen based on simple arithmetic, half of the required delay (100 seconds) would be allotted each to the human and technical communications elements. A transaction is defined as a two-way exchange between the end users.

Step 2: Continuation of the simplistic approach would allocate half of the 100 seconds, or 50 seconds, to each direction of communication.

Step 3: Reference [G- 1] provides performance data for an HF Data Link system complying with Chapter 11 SARPs. Linearly interpolating from data in [G- 1] for a minimum (600 bps) avionics installation and an ATN data link environment, the 50-second requirement for each direction would be met with a maximum message length of about 13 octets in the from-aircraft direction and 380 octets in the to-aircraft direction. While the 380 octets in the to-aircraft direction may be adequate for a response from the ground side, the 13-octet limit in the from-aircraft direction might constitute an impossible constraint. Note from [G- 1] that, even if the from-aircraft direction were allotted the entire 100 seconds of technical delay by throttling the from-aircraft direction, the maximum message length would be only 29 octets.

Case 2 -- Convolution Approximation Approach

Step 1: Instead of simplistic subtraction and division, suppose it is recognized that the human and the data link element transfer delays are probability distributions, manipulation of which requires some care. Even if the distributions were known, closed-form "deconvolution" is not possible, although iterative solution techniques could be employed. Alternatively, the approximation of Eq. [G- 4] can be directly applied by setting PTOTAL(95) = 200 (the end-to-end requirement), P2(95) = P1(95), and solving for P1(95). As P2(95) = P1(95), the result is approximately 117 seconds for each of the two elements.1

Step 2: Application of Eq. [G- 4] to the technical element allotment for 117 seconds, from Step 1, provides a 95^{th} -percentile result of a 68-second allotment to each direction of transmission in the transaction.

Step 3: Referring to [G- 1] as in Step 3 of Case 1, it is seen that a 68-second 95^{th} -percentile delay will support about 19 octets in the from-aircraft direction, and about 510 octets in the to-aircraft direction.

Case 3 --Improvement through Link Balancing

Now, suppose the directional transfer delay asymmetry of the system apparent in [1] were recognized, and a better-balanced allocation were made for the two directions. From the perspective of the initiator of a transaction, it makes no difference whether or not the delay is equal in both directions (and currently developing RCP standards impose no distinction).

Case 3a -- Simplistic Approach

It is noted that a substantial difference exists in maximum message length supported in each direction in Case 1, Step 3, due to the equal allotment of delay (100 seconds) to each direction of Case 1, Step 2. Further study of [1] might suggest an allocation of, say, 75 seconds for the from-aircraft direction. This value would support a maximum message lengths of 21 octets in the from-aircraft direction, which might be usable for a highly-compressed message. The remainder, 100 - 75 = 25 seconds, would be allotted to the to-aircraft direction, supporting a message length of 120 octets, which might still be adequate.

1 Solution of Eq. F-4 as described yields two possible roots -- 117.2 and 682.84 -- . As the latter is greater than the input data, clearly the correct solution is 117.2.

Because the 95% transfer delay rapidly of [G- 1] increases with message length in the from-aircraft direction, little more would be gained in either direction by finer-grained balancing.

Case 3b -- Convolution Approximation Approach

The approximate convolution approach of Case 2 establishes an total allotment of 117 seconds for the technical transfer delay in both directions. Using the same approach as in Case 3a above, 30 seconds might be allotted to the from-aircraft direction. Applying the inverse convolution approximation of Eq. [G- 4] as in Case 2, Step 1, 100 seconds can be allotted to the to-aircraft direction while maintaining an overall delay of 117 seconds. From Eq. [G- 1], the from-aircraft direction would support a 29-octet message length, and the to-aircraft direction would support a 180-octet message length.

G.9 Conclusions

The results of each illustration case in Section G.8 are summarized below.

Case	From-Aircraft Max. Message Length	To-Aircraft Max. Message Length
1 - Simplistic Approach	13	380
2 - Convolution Approximation	19	510
3a - Simplistic Link Balancing	21	120
3b - Convolution Approximation with Link Balancing	29	180

The characteristics of the HF Data Link system of Eq. [G- 1] are such that the "bottleneck" lies in the from-aircraft direction, which may be true of other systems because of the nature of the multiple aircraft-to-ground station, multi-point-to-point link.2 The opposite direction is point-to-multi-point, which can be more efficiently ordered.

In view of that characteristic, a comparison of Case 1 with Case 3b is a rather dramatic illustration of the consequences of inappropriate and unrealistic partitioning and allocation. In effect, the combination of appropriate analytical approaches provides a from-aircraft capacity that could not be achieved using the simplistic approach even by allocating all of the delay to that direction, and completely choking the reverse direction, whereas an appropriate methodology demonstrates a substantial capacity also in the reverse direction. Further, the convolution approximation method indicates that conservative analyses have been performed, as the method underestimates the projected performance.

Reference

[G- 1] DO-215A, *Guidance on Aeronautical Mobile Satellite Service (AMSS) End-to-End System Performance*, Washington: RTCA, Inc., 1995, Section 2.1.3.

2 The Reference [G-1] from-aircraft transfer delay *vs*. message length characteristics are non-linear, due to the nature of the channels. The linear interpolations used in the illustrations of this section may have significant inaccuracy at certain points throughout the transfer characteristic. However, any error in the interpolations is on the pessimistic side of projected performance.